中国科学技术大学
University of Science and Technology of China

MeV astronomy on low energy cosmic rays and on-going MeV projects in China

Ruizhi Yang (USTC)

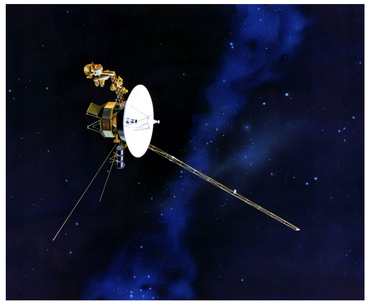
MeV astronomy on LECRs

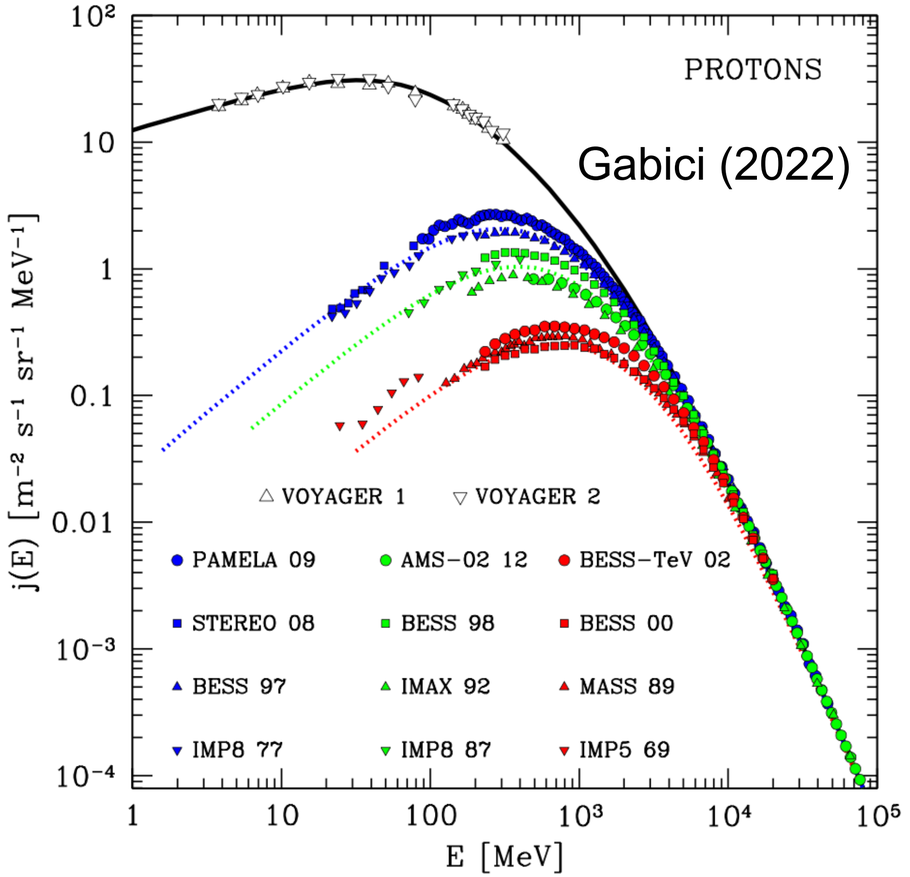
Low-energy Cosmic Rays

LECRs (E <1 GeV/nucleon)

Significantly contribute the ionization and heating of the gas and the energy balance of the ISM, play an important role on the star-forming process

- **Indirect study**:
  ionization rate, non-thermal X-ray emission (6.4 KeV Fe Kα line) …
- **Direct observations**:
  very difficult, solar modulation,
  Measurements of Voyager 1 and 2 cannot represent the property of LECRs in the Galaxy…





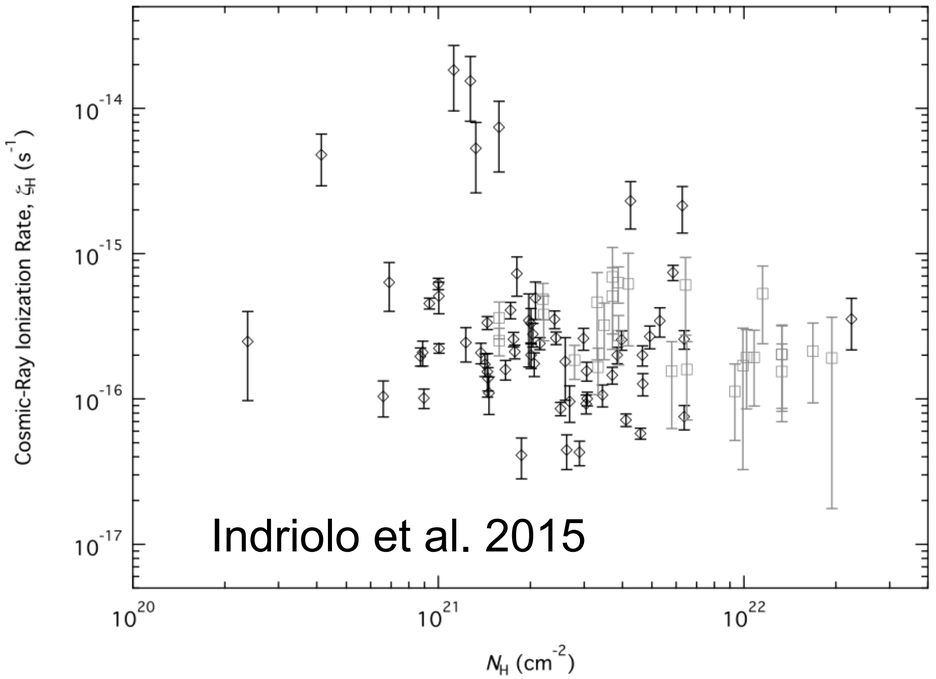
Due to slower diffusion and faster energy loss, the distribution of LECRs in our Galaxy should be more inhomogeneous than high-energy CRs.

Low-energy Cosmic Rays

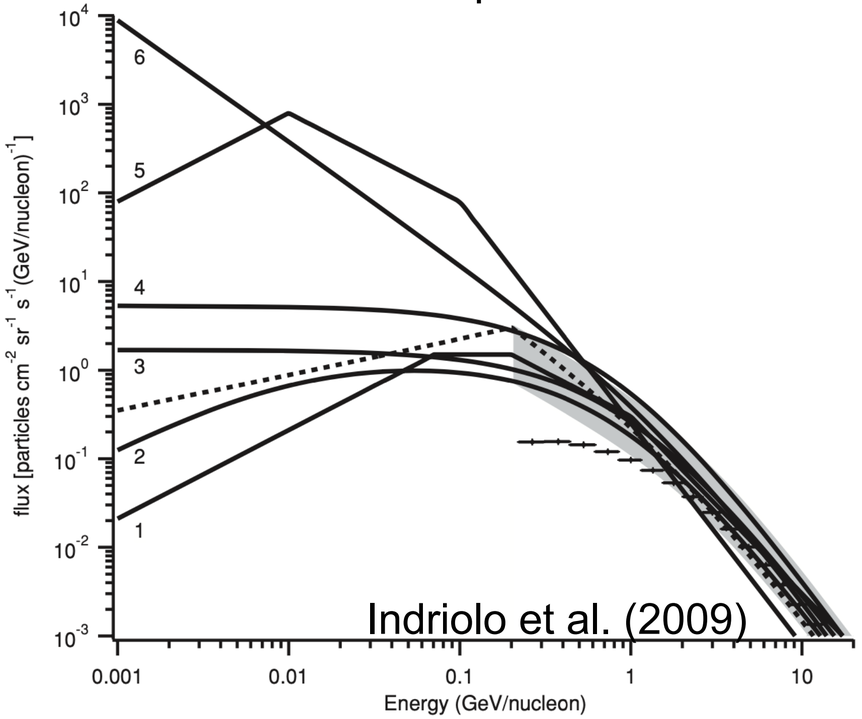
CR ionization rate measured in Galactic diffuse molecular clouds: from 10^{-16} s^{-1} to 10^{-14} s^{-1}

>>the one which is calculated for the standard CR flux thought to be produced by DSA in SNRs (10^{-17} s^{-1})

An additional LECR nuclei component in our Galaxy ???



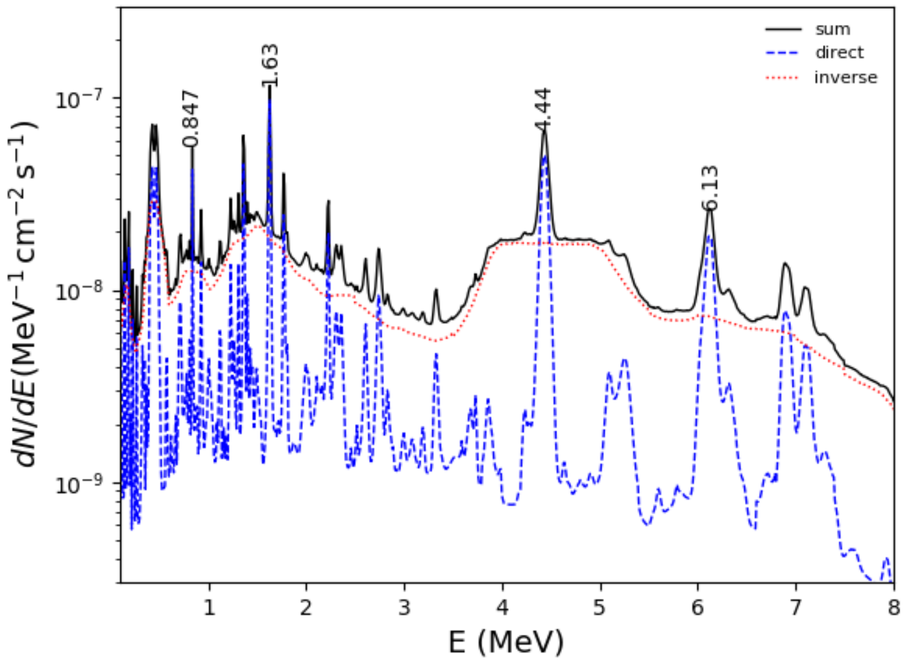
Example CR spectra used in the literature over the past few decades.



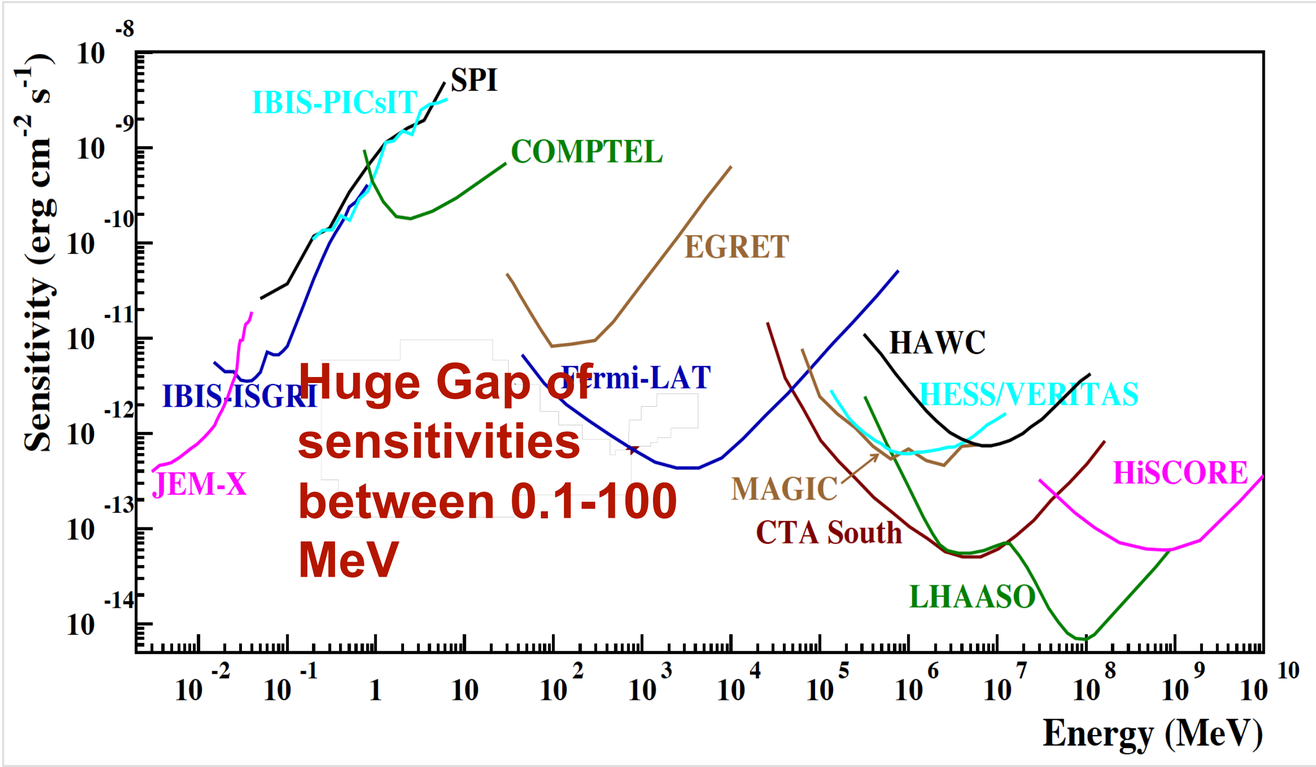
However, neither the nature - electrons or nuclei - nor the spectrum of the LECR component can be deduced from the measurements of ionization rate.

Nuclear de-excitation line emission from LECRs

Nuclear de-excitation line emission:
distinguish nuclei & electrons, provide information of the LECRs and the medium.



12C : 4.44 MeV 16O : 6.13 MeV **(~0.1-10 MeV)**



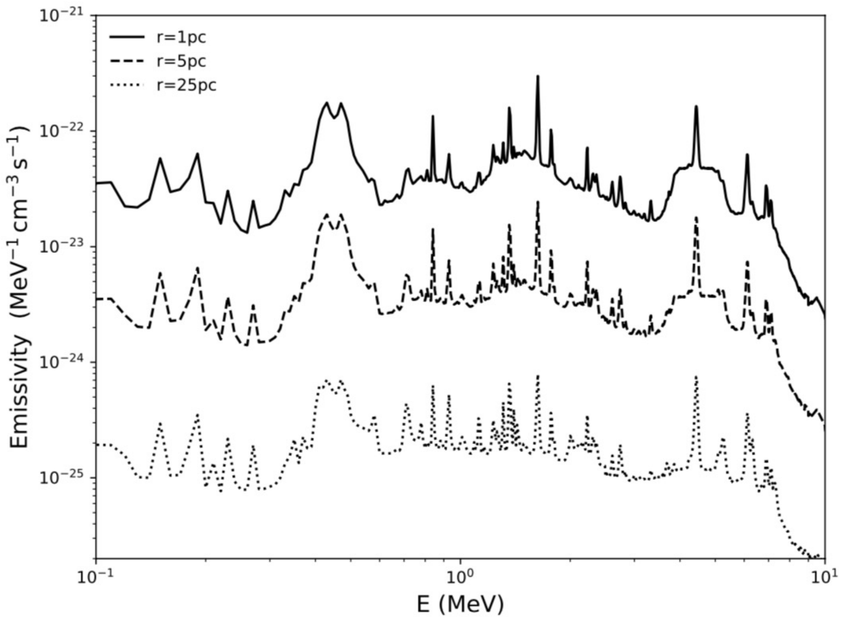
Proposed or ongoing MeV gamma-ray projects in recent years:

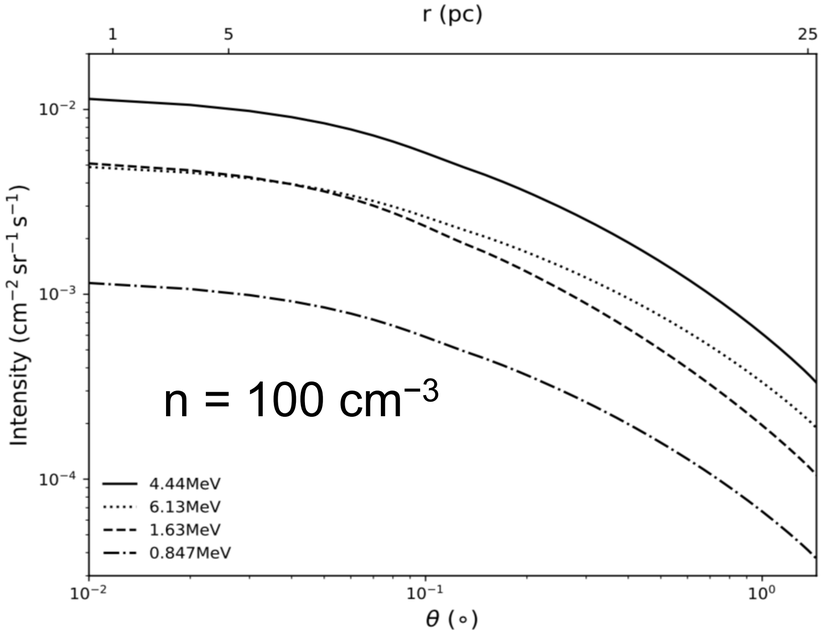
MeGaT, MASS, MeVGRO,MeVCube, e-ASTROGAM, AMEGO, COSI, GRAMS, GECCO, HARPO,SMILE…

MeV nuclear line emission from a hypothetic CR source

A point source that continuously injecting CRs , Q=1e38 erg s^{-1}, d=1 kpc, spectra index s=2.0
Elemental Composition: CR (Voyager) + medium (solar)

The line fluxes drop sharply with θ, almost negligible at θ~1.5° (r~25 pc)





Integrated 4.44 MeV line flux

n (cm^{-3})	χ	Flux (photon cm^{-2} s^{-1})
1	1.0	5.49×10^{-9}
1	0.1	3.25×10^{-8}
1	0.01	1.25×10^{-7}
100	1.0	1.25×10^{-7}
100	0.1	3.16×10^{-7}
100	0.01	5.96×10^{-7}

Point-like emission given the angular resolution of next-generation MeV γ-ray detectors.
For the detection, sensitivity requirement: 10^{-6} to10^{-7} ph cm^{-2} s^{-1}

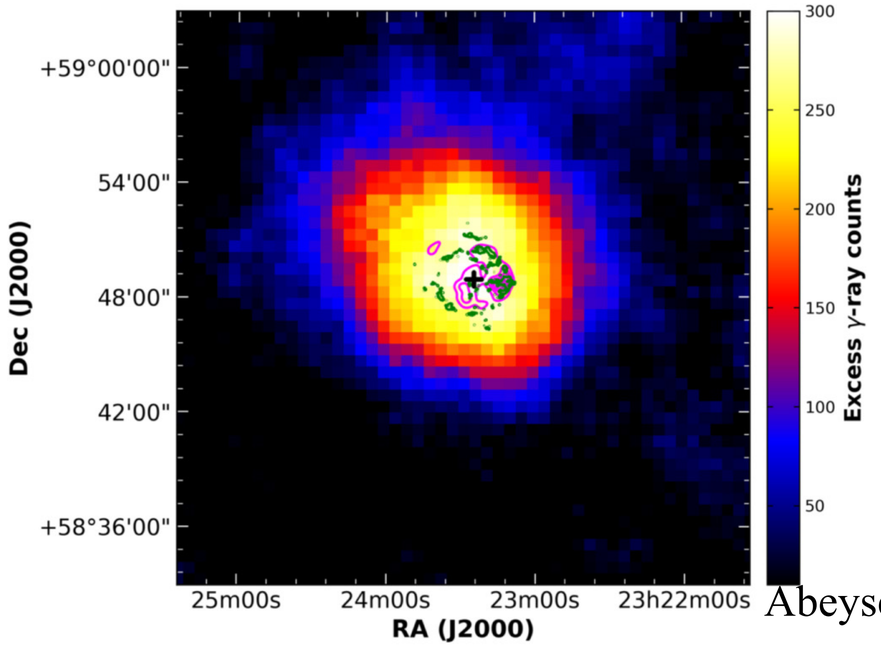
B. Liu, R.-z. Yang and F. Aharonian, 2021, A&A

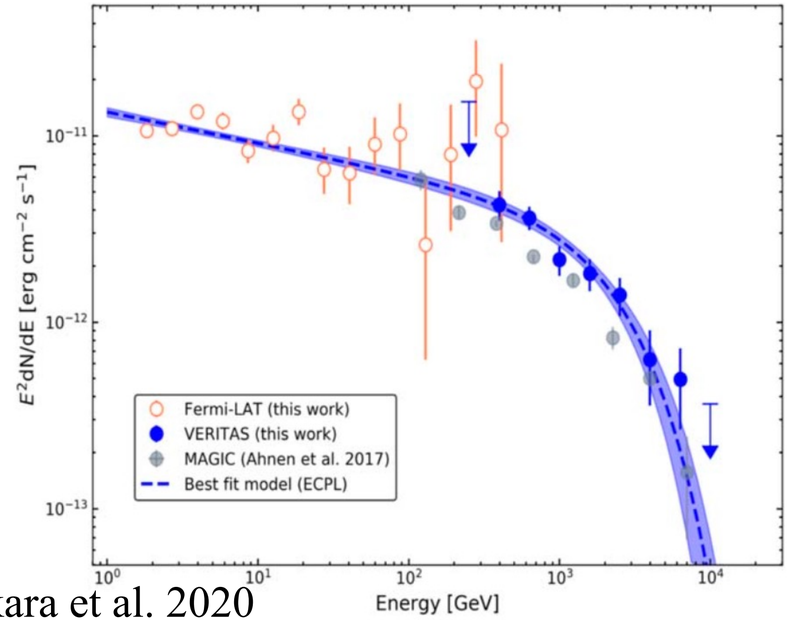
SNR Cas A

Cassiopeia A: a young remnant of a core-collapse SN exploded ~ 340 yrs ago.
distance: ~3.4 kpc radius: 2.5 pc (2.5')



Chandra X-ray Image of Cas A
Credit: NASA/CXC/SAO





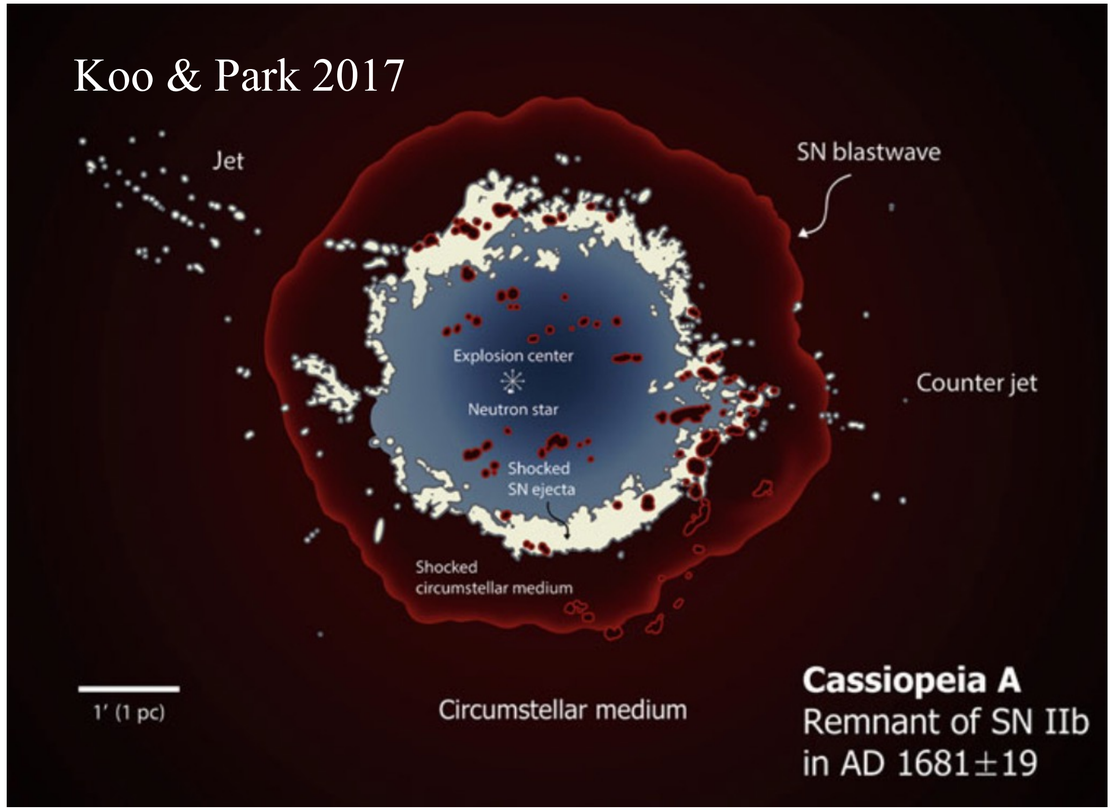
Abeysekara et al. 2020

The origin of these GeV-TeV γ-rays: hadronic, leptonic, hadronic+leptonic ?

Most studies show that a hadronic components is needed. (e.g. Abdo et al. 2010; Yuan et al. 2013; Zirakashvili et al. 2014; Ahnen et al. 2017; Zhang & Liu 2019; Abeysekara et al. 2020)

The GeV-TeV gamma-rays emission can constrain the fluxes of the high energy nuclei.

New estimation of the nuclear de-excitation line emission from SNR Cas A



Schematic picture of SNR Cas A

White and *blue colours* represent SN material;

red color represents the CSM

	CR [a] n_{el}/n_H	Solar [b] n_{el}/n_H	CSM [c] $n_{el}/n_\odot$	Ejecta [d] n_{el}/n_O
H	1	1	1	0.01-0.05*
He	8.140×10^{-2}	8.414×10^{-2}	3	0.1-0.5*
C	1.671×10^{-3}	2.455×10^{-4}	1	0.5*
N	2.444×10^{-4}	7.244×10^{-5}	15	0.1*
O	1.570×10^{-3}	5.370×10^{-4}	1	1
Ne	1.507×10^{-4}	1.122×10^{-4}	1	0.02
Mg	2.264×10^{-4}	3.467×10^{-5}	1	0.005
Si	1.898×10^{-4}	3.388×10^{-5}	1	0.05
S	2.087×10^{-5}	1.445×10^{-5}	1	0.05
Ar	4.554×10^{-6}	3.162×10^{-6}	1	0.005
Ca	1.195×10^{-5}	2.042×10^{-6}	1	0.004*
Fe	1.152×10^{-4}	2.884×10^{-5}	1	0.005

[a] Number density ratio relative to H, adopted from the Voyager measurement of local LECR abundance (see Cummings et al. 2016, Table 3).

[b] Number density ratio relative to H, adopted the recommended present-day solar abundance (see Lodders 2010, Table 6).

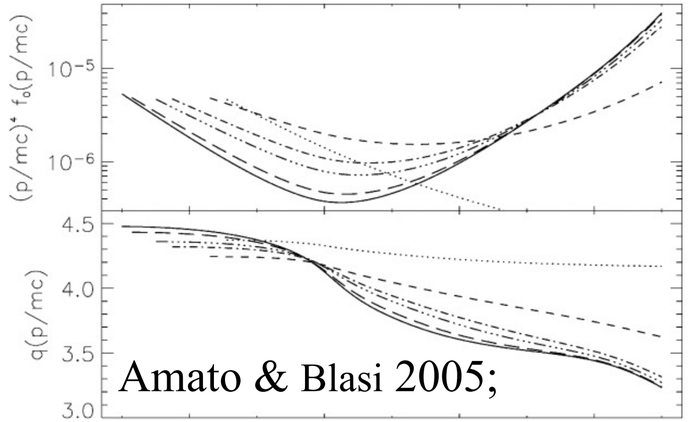
[c] Number density ratio relative to the solar value, adopted for the CSM of Cas A, mainly referred to Hwang & Laming (2012).

[d] Number density ratio relative to O, mainly adopted from Docenko & Sunyaev (2010).

New estimation of the nuclear de-excitation line emission from SNR Cas A

Studies of nonlinear shock acceleration predict that the spectra of the accelerated particles show some concavity in momentum space.

The nuclei spectra: $\sim p^{-4}$, at low energies, flatter than p^{-4} at the highest energies. (e.g., Amato & Blasi 2005; Caprioli et al. 2011).



Amato & Blasi 2005;

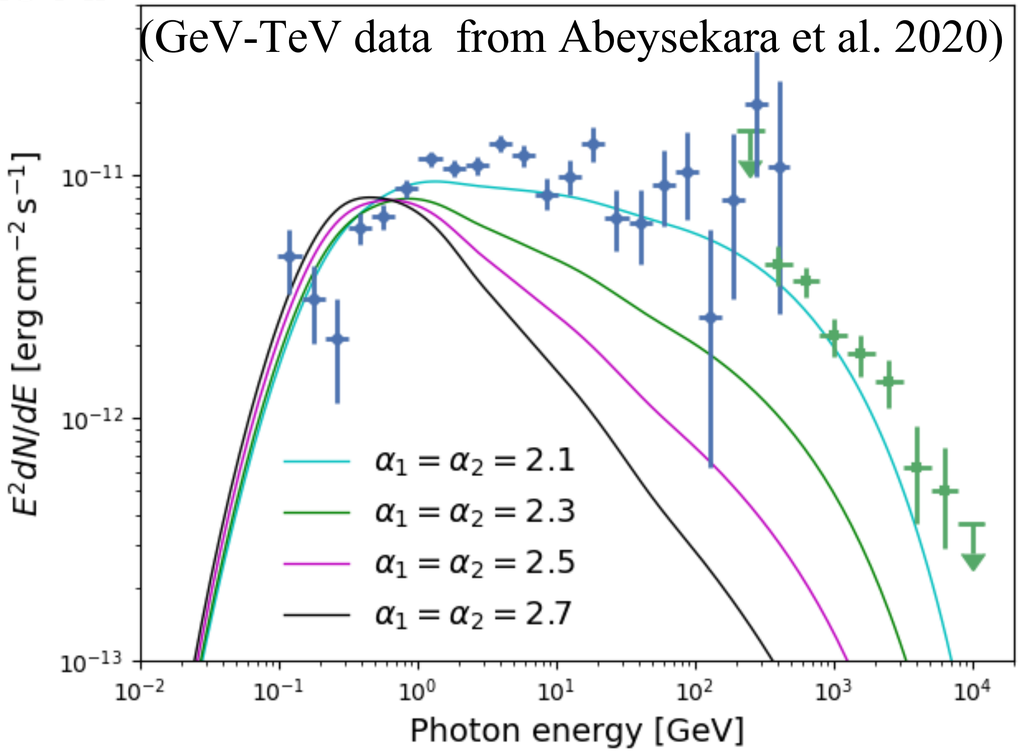
Spectral distribution of protons accelerated by Cas A: (simplified assumption)

$$F(E)=\begin{cases} N_0 \left[\frac{p(E)}{p(E_b)}\right]^{-\alpha_1} \exp\left[\frac{-p(E)}{p(E_{cut})}\right], & \text{if } E \geq E_b \\ N_0 \left[\frac{p(E)}{p(E_b)}\right]^{-\alpha_2} \exp\left[\frac{-p(E)}{p(E_{cut})}\right], & \text{if } E < E_b \end{cases}.$$

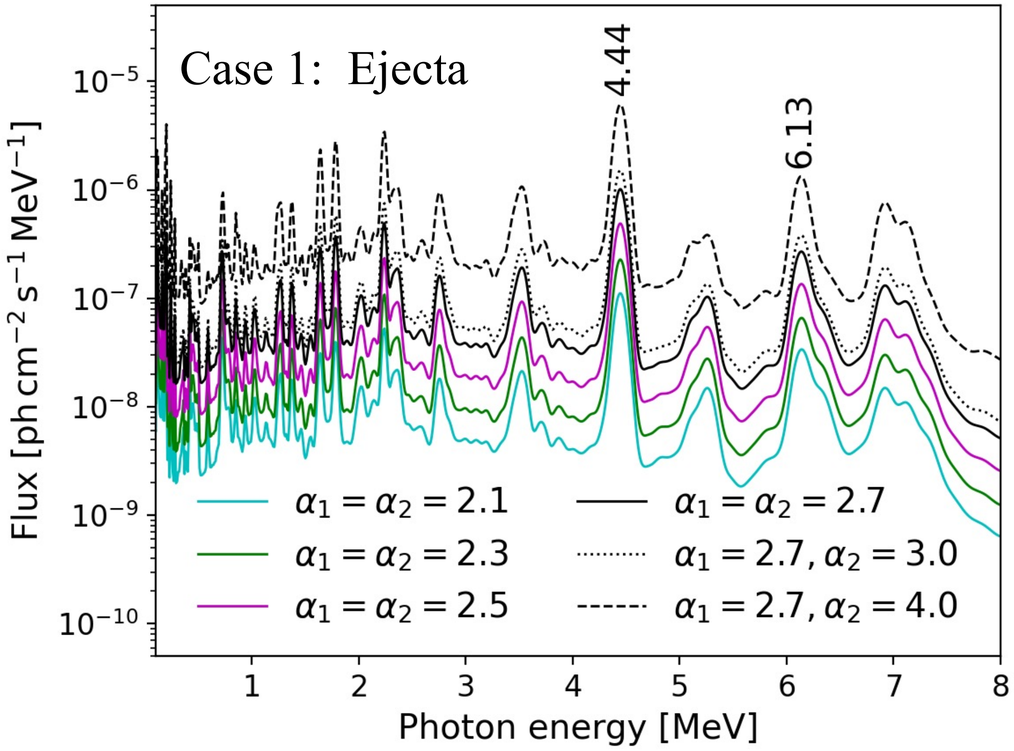
E_{cut}= 10 TeV, E_b=0.2 GeV,

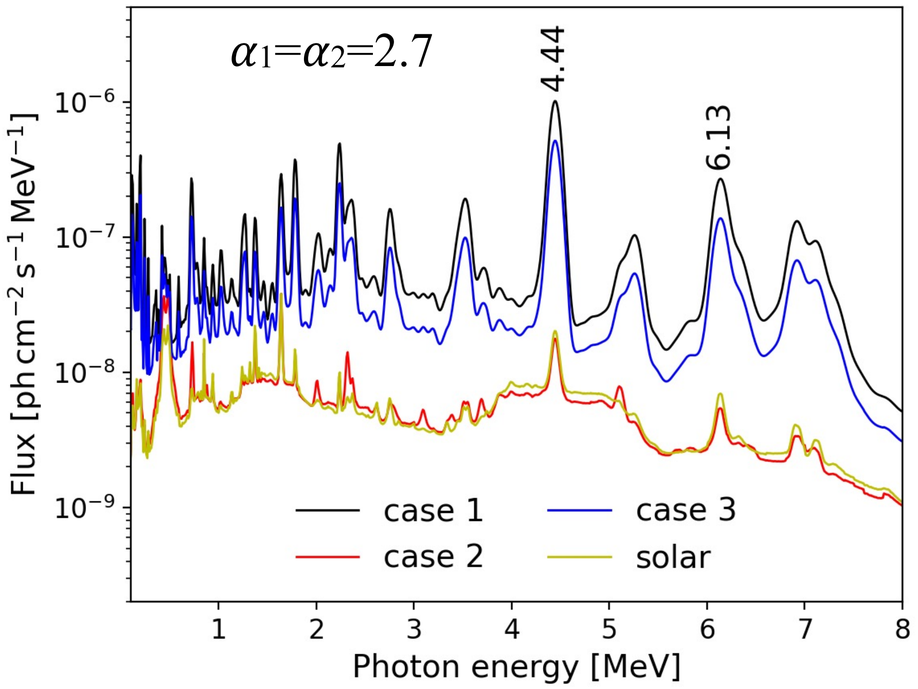
α_1=2.0 — 2.7, α_2=α_1, 3.0, 4.0

(GeV-TeV data from Abeysekara et al. 2020)



New estimation of the nuclear de-excitation line emission from SNR Cas A





$$F(E)=\begin{cases} N_0\left[\frac{p(E)}{p(E_b)}\right]^{-\alpha_1}\exp\left[\frac{-p(E)}{p(E_{cut})}\right], & \text{if } E \geq E_b \\ N_0\left[\frac{p(E)}{p(E_b)}\right]^{-\alpha_2}\exp\left[\frac{-p(E)}{p(E_{cut})}\right], & \text{if } E < E_b \end{cases}.$$

α_1=2.0–2.7, α_2=α_1, 3.0, 4.0

Integrated 4.44 MeV and 6.13 MeV line fluxes of various cases

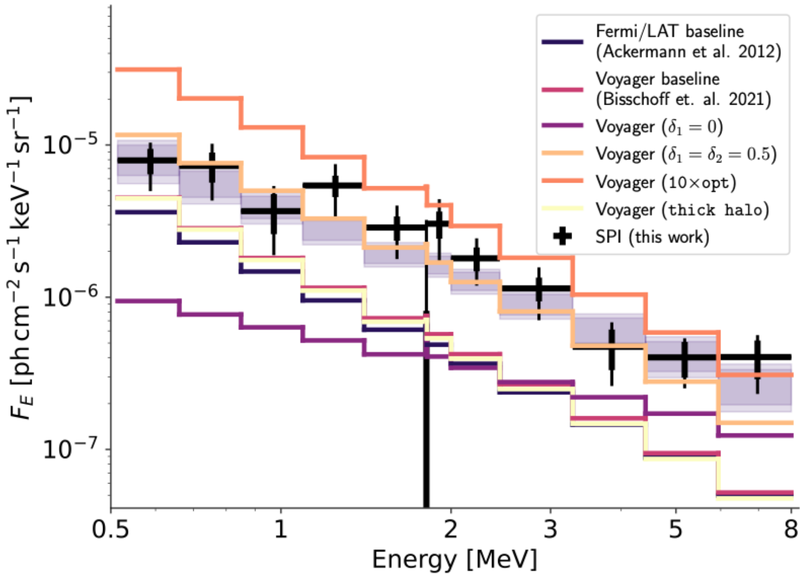
	Medium	4.44 MeV	6.13 MeV
case 1	Ejecta	$(0.09–7.71)\times10^{-7}$	$(0.04–2.10)\times10^{-7}$
case 2	CSM	$(0.10–8.84)\times10^{-9}$	$(0.04–2.66)\times10^{-9}$
case 3	Ejecta+CSM	$(0.05–3.93)\times10^{-7}$	$(0.02–1.06)\times10^{-7}$

B. Liu, R.-z. Yang*, X.-y. He and F. Aharonian, 2023, MNRAS

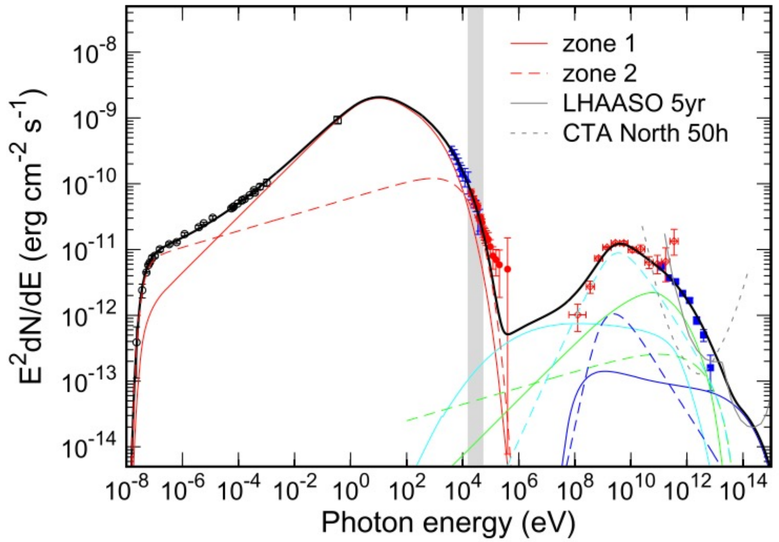
New estimation of the nuclear de-excitation line emission from SNR Cas A

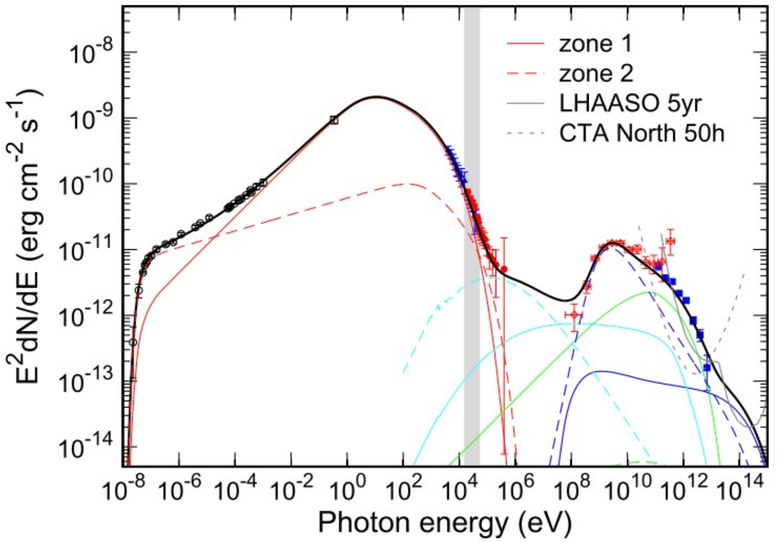
MeV continuum background

- Diffuse Galactic emission: new results from the analysis with the spectrometer SPI aboard INTEGRAL in the range of 0.5–8.0 MeV around the Galactic center (Siegert et al. 2022) .
- MeV continuum emission from Cas A: mainly non-thermal bremsstrahlung from electrons, predicted energy fluxes <~$6e^{-12}$ erg cm^{-2} s^{-1} @ MeV from different scenarios on the origin of the GeV-TeV emission.



Siegert et al. 2022



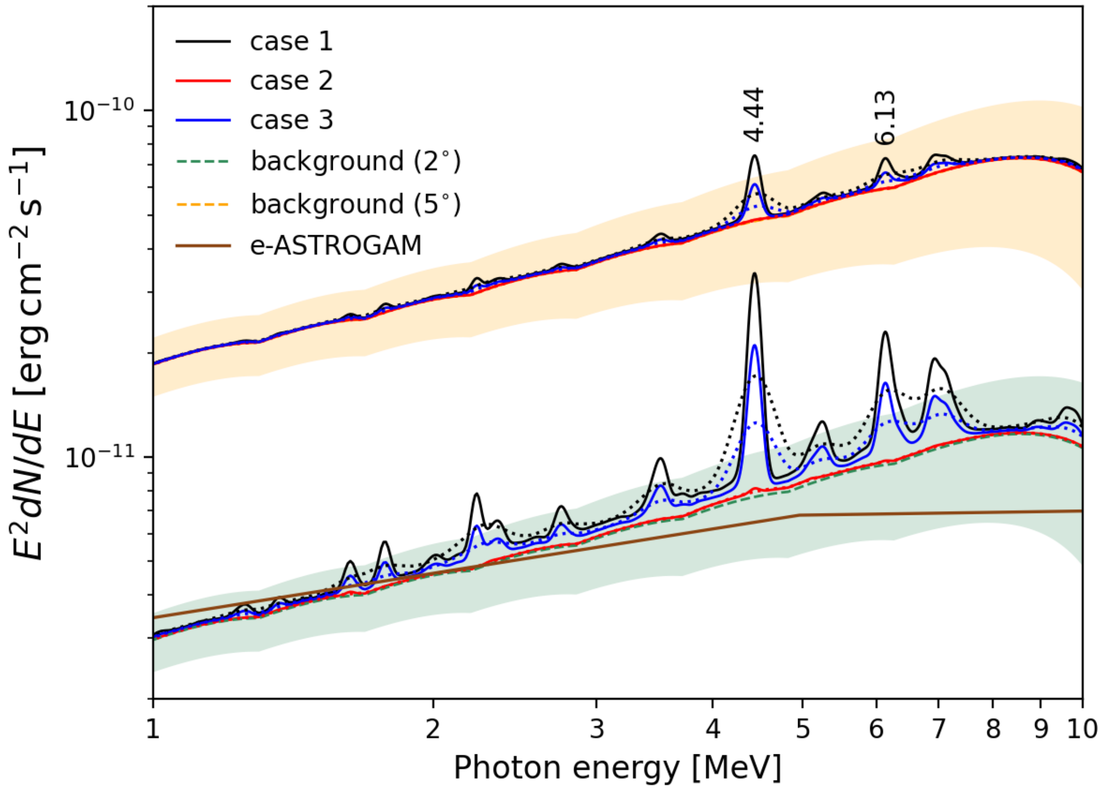


Zhang & Liu 2019

New estimation of the nuclear de-excitation line emission from SNR Cas A

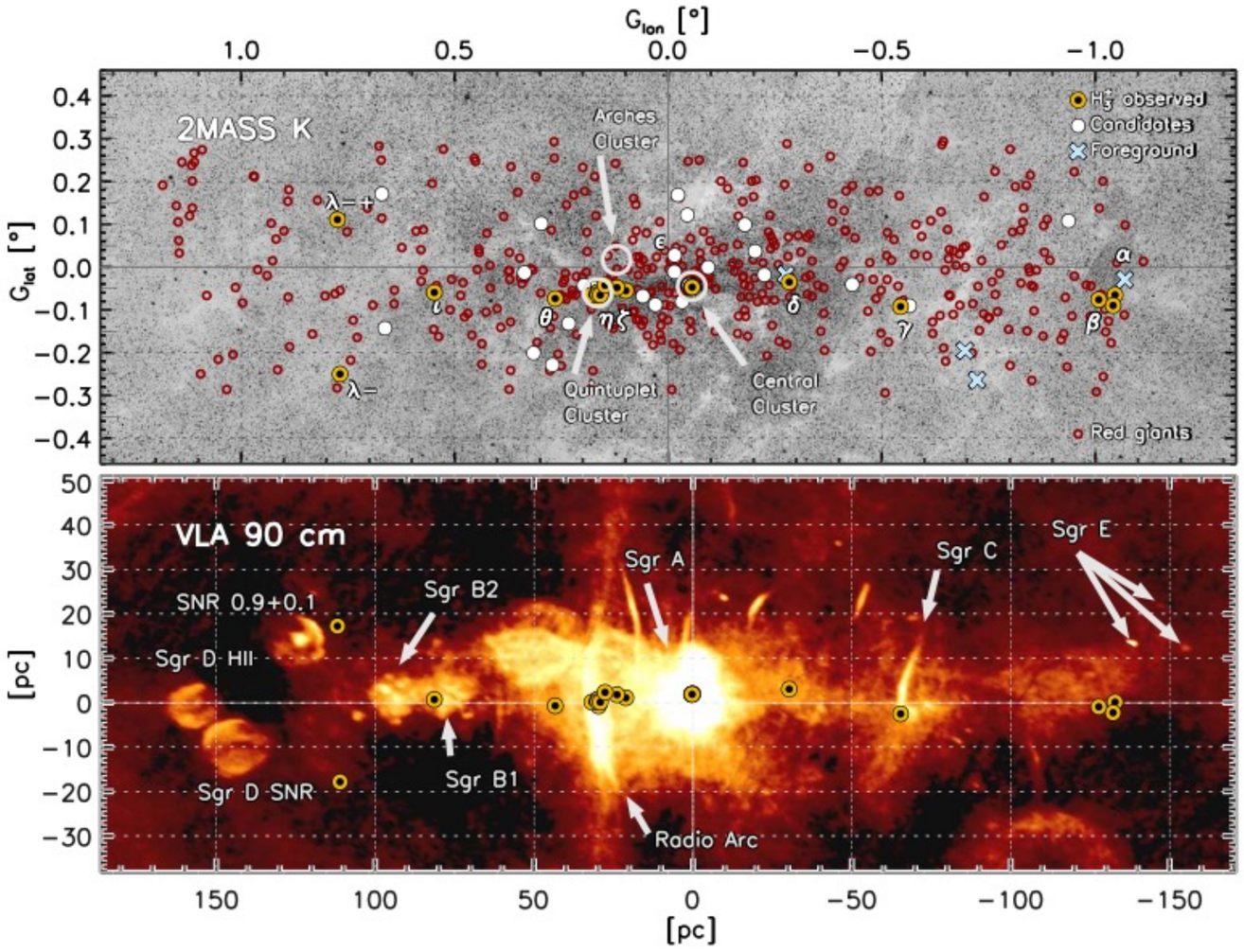
Detectability of the next-generation MeV detectors: energy resolution

The overall MeV γ-ray emission from Cas A region with extrapolated diffuse background added ($\alpha_1 = \alpha_2 = 2.7$)
solid lines: $\Delta E/E = 2\%$
dotted lines: $\Delta E/E = 10\%$



B. Liu, R.-z. Yang∗, X.-y. He and F. Aharonian, 2023, MNRAS

Probe the LECRs in the center molecular zone (CMZ)



Oka et al. (2019)

Measured ionization rate in the CMZ :

Oka et al. 2019: ~ 2×10^{-14} s^{-1}

Indriolo et al. 2015: ~ 10^{-14} s^{-1}

Le Petit et al. 2015 ~ $>= 10^{-14}$ s^{-1}

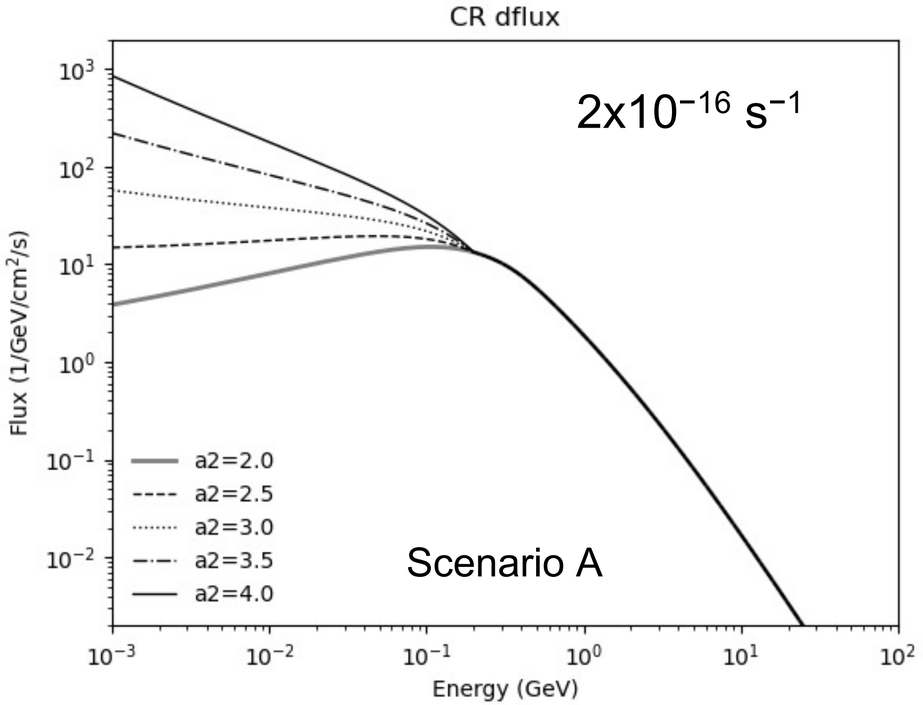
- Origin of the high ionization rate: LECR proton, electron.. ? Additional component of LECRs may be needed
- Local LECR accelerators: star clusters, star-forming region, MBH, protostellar winds/jets
- PSF of next-generation of MeV telescope (MeGaT) ~2 °, the CMZ region can be seen as a point-like source.

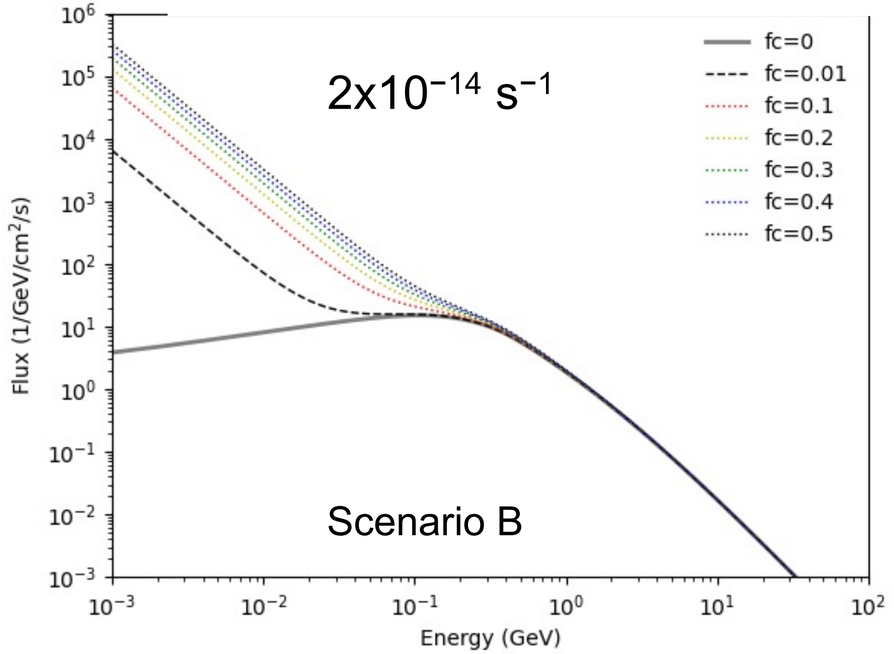
Probe the LECRs in the center molecular zone (CMZ)

Scenario A: continuous injection $Q_{\rm in}$ (piecewise power-law distribution, $E_{\rm b}$ = 0.2 GeV, α1 = 2.0, and α2 =2.0, 2.5, 3.0, 3.5, and 4.0)
Scenario B: continuous injection $Q_{\rm in}$ (simple power-law distribution, α1 = α2 = 2.0) and a local carrot component $Q_{\rm c}(E)$ (α = 4, $E_{\rm cut}$ =1, 2, 4, and 10 MeV, $f_{\rm c}$ for different enhancements of LECRs)

$$Q_{\rm in}(E) = \begin{cases} Q_0 \left[\frac{p(E)}{p(E_{\rm b})}\right]^{-\alpha_1}, & \text{if } E \geq E_{\rm b} \\ Q_0 \left[\frac{p(E)}{p(E_{\rm b})}\right]^{-\alpha_2}, & \text{if } E < E_{\rm b} \end{cases}.$$

$$Q_{\rm c}(E) = \begin{cases} f_{\rm c} Q_{\rm lb}(E_{\rm b}) \left[\frac{p(E)}{p(E_{\rm b})}\right]^{-\alpha}, & \text{if } E \geq E_{\rm cut} \\ 0, & \text{if } E < E_{\rm cut} \end{cases}.$$

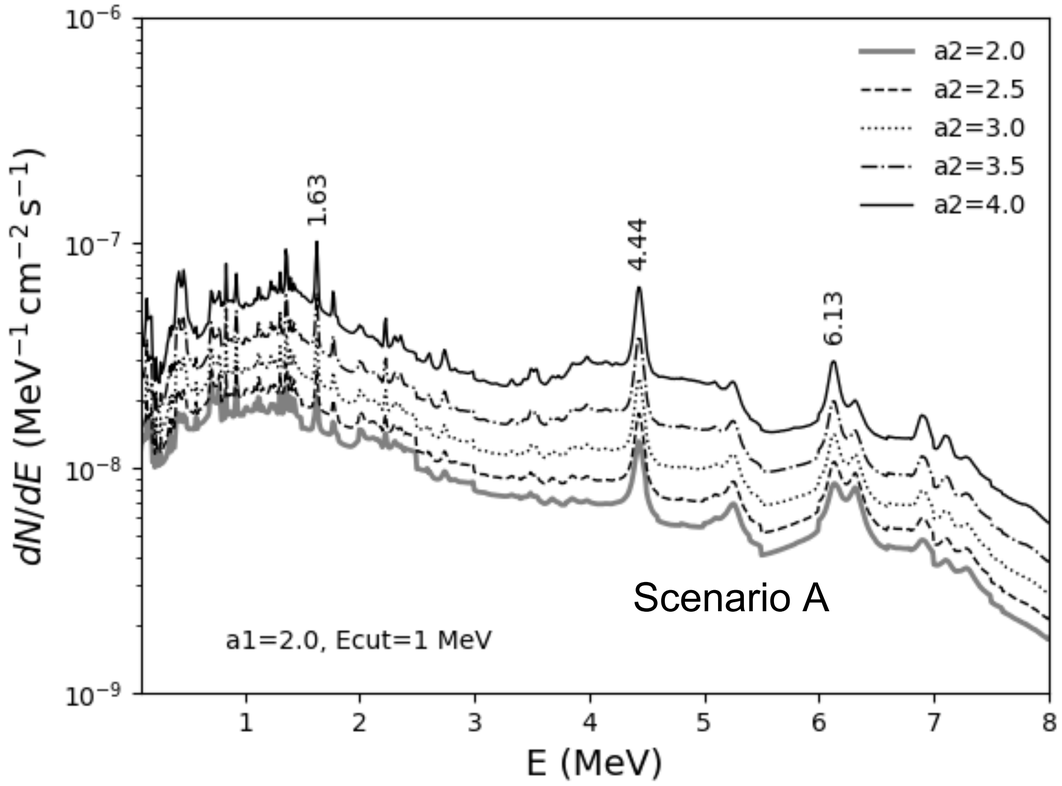


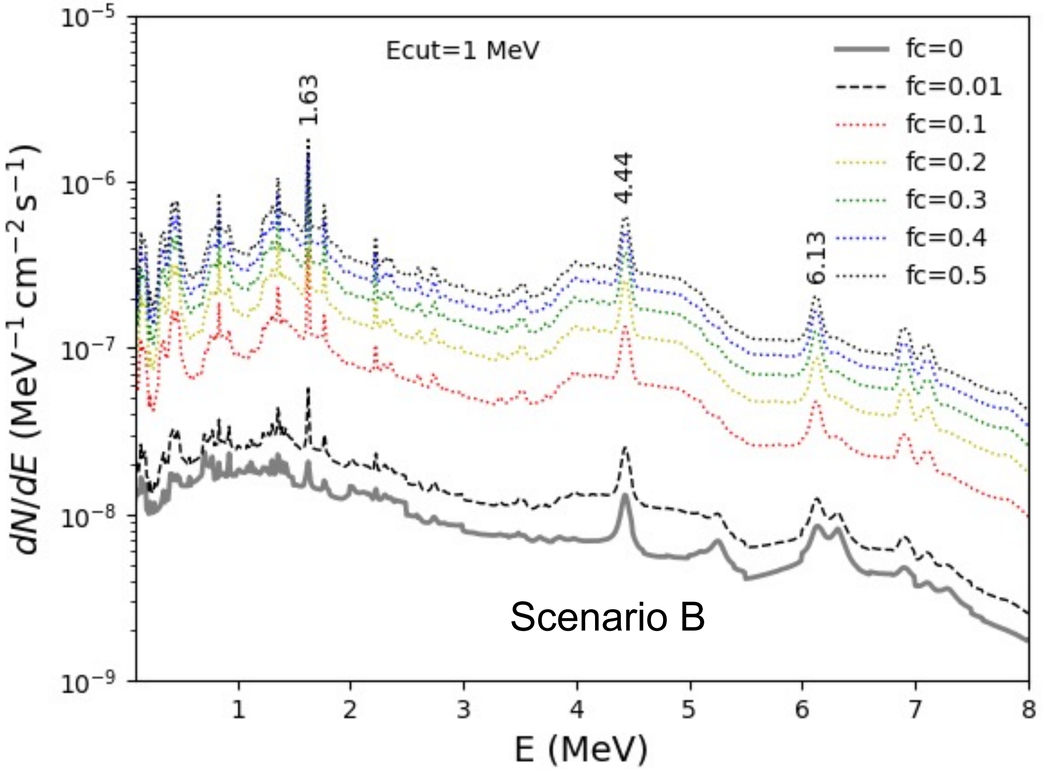


B. Liu & R.-z. Yang (PRD, 2024)

Probe the LECRs in the center molecular zone (CMZ)

Estimated MeV nuclear de-excitation line emission for different scenarios

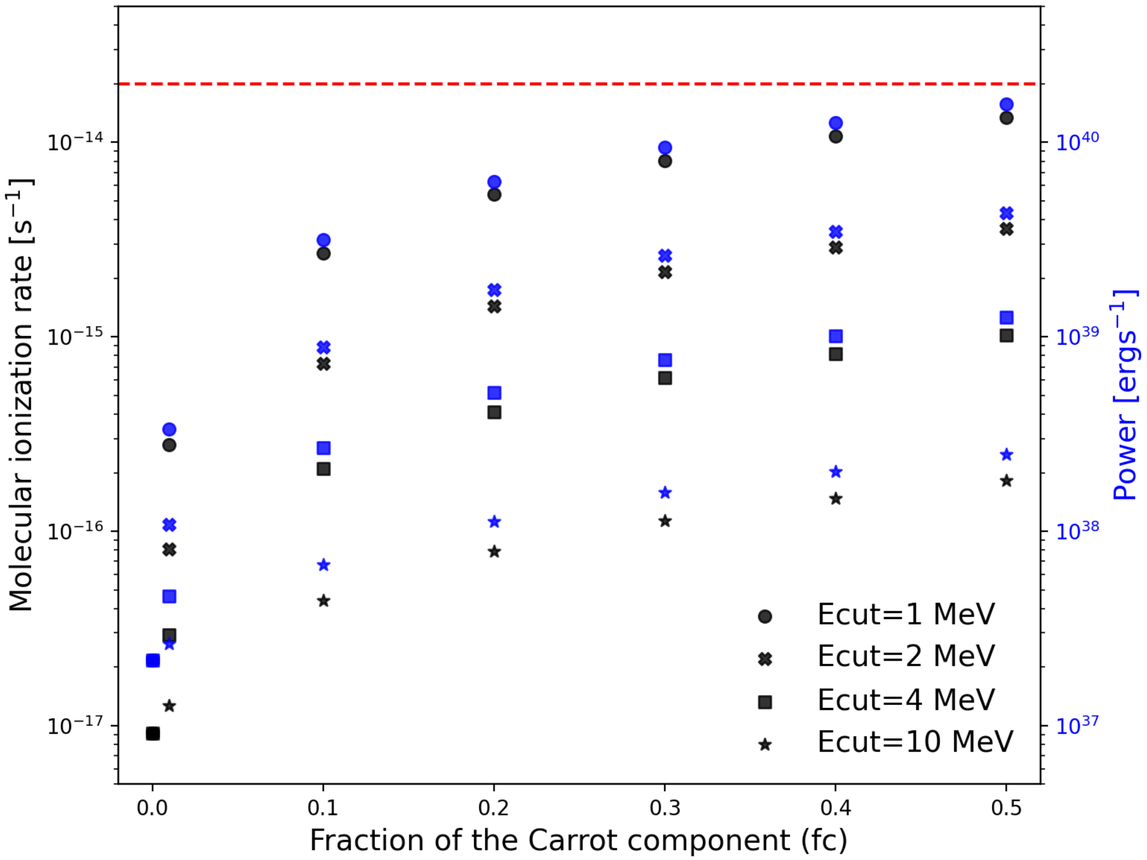


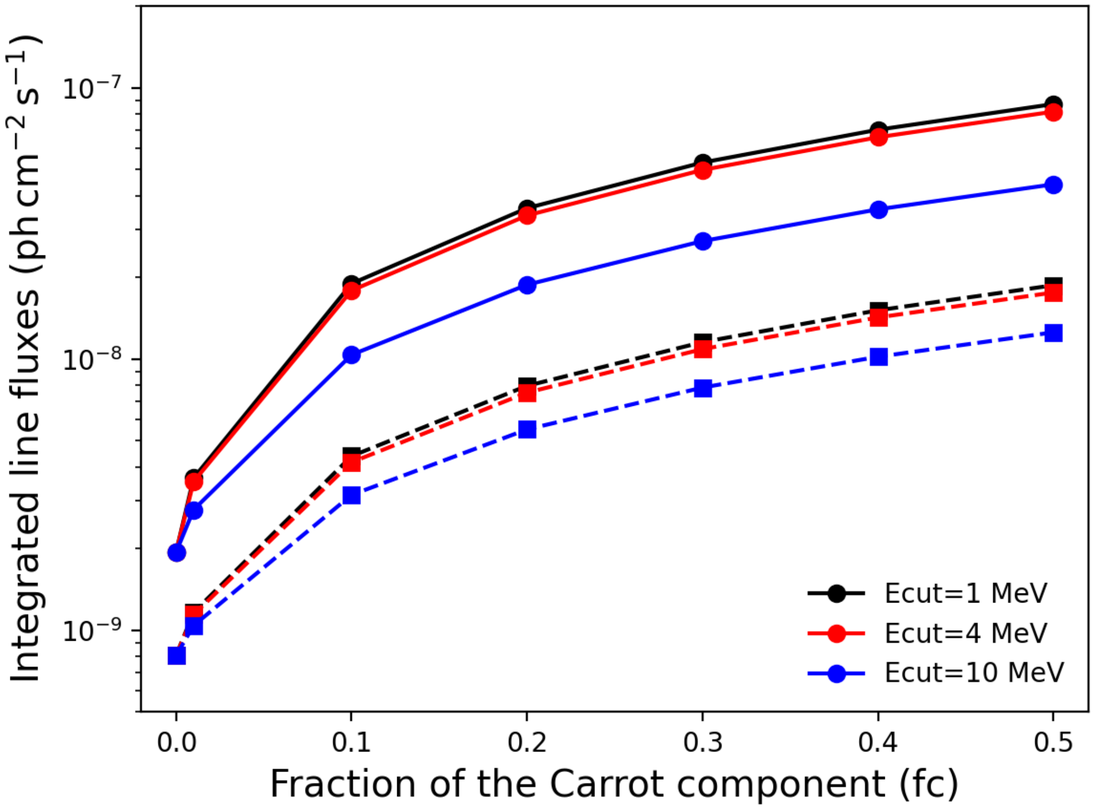


B. Liu & R.-z. Yang (to be submitted)

Probe the LECRs in the center molecular zone (CMZ)

Ionization rate, power and integrated line fluxes for additional LECR component (Carrot)

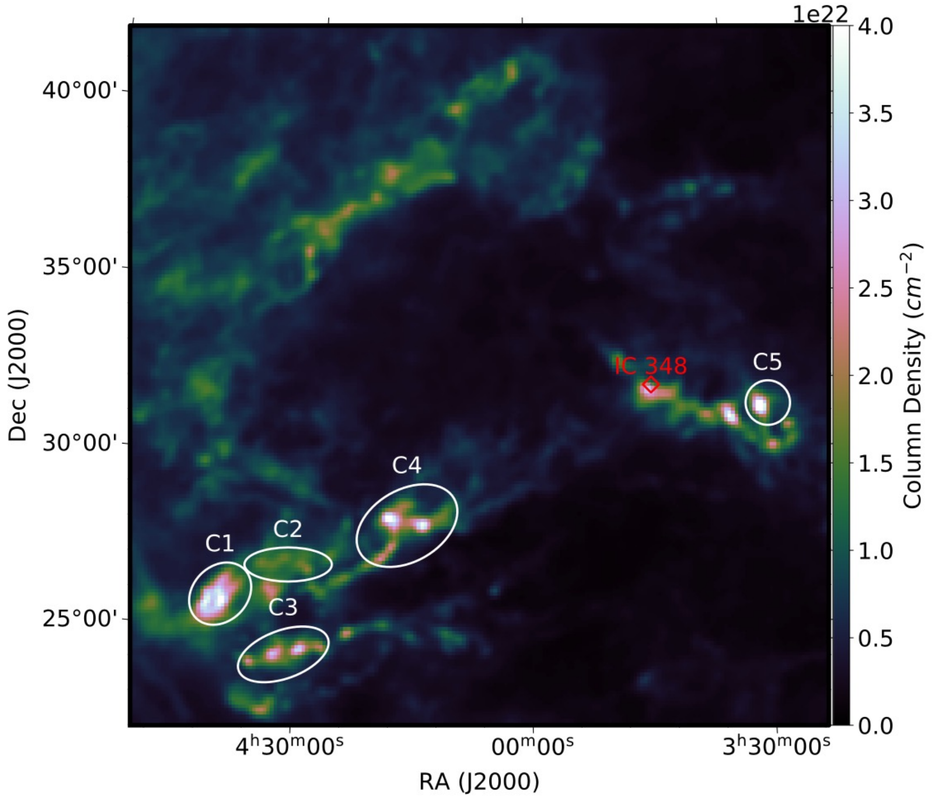




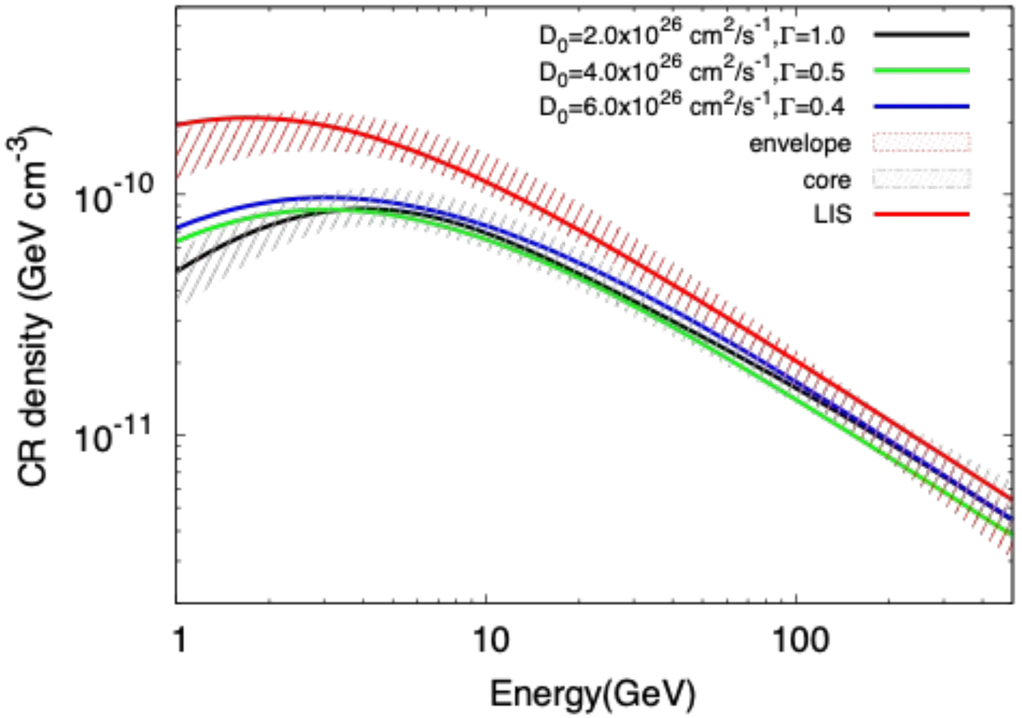
B. Liu & R-z Yang (to be submitted)

Study the propagation of CRs in giant molecular clouds (GMC)

Effective shielding of ≲10 GeV cosmic rays from dense molecular clumps (Yang et al. 2023, NA)



The total column density (in units of cm^{-2}) distribution of Taurus and Perseus molecular clouds, derived from the Planck dust opacity map.



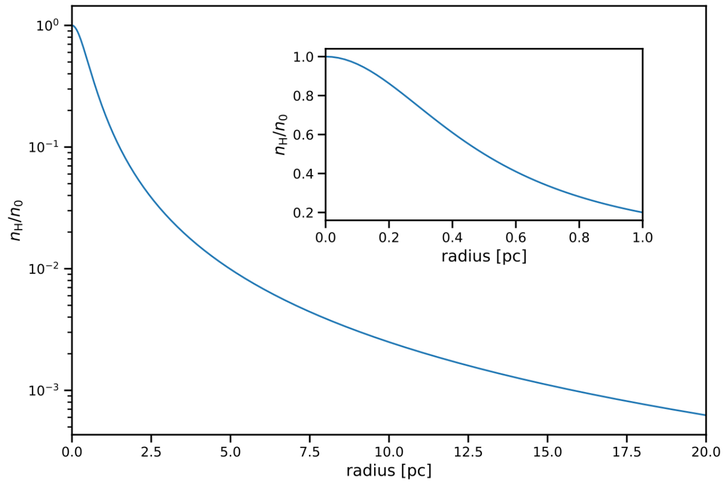
The derived CR energy density distribution.

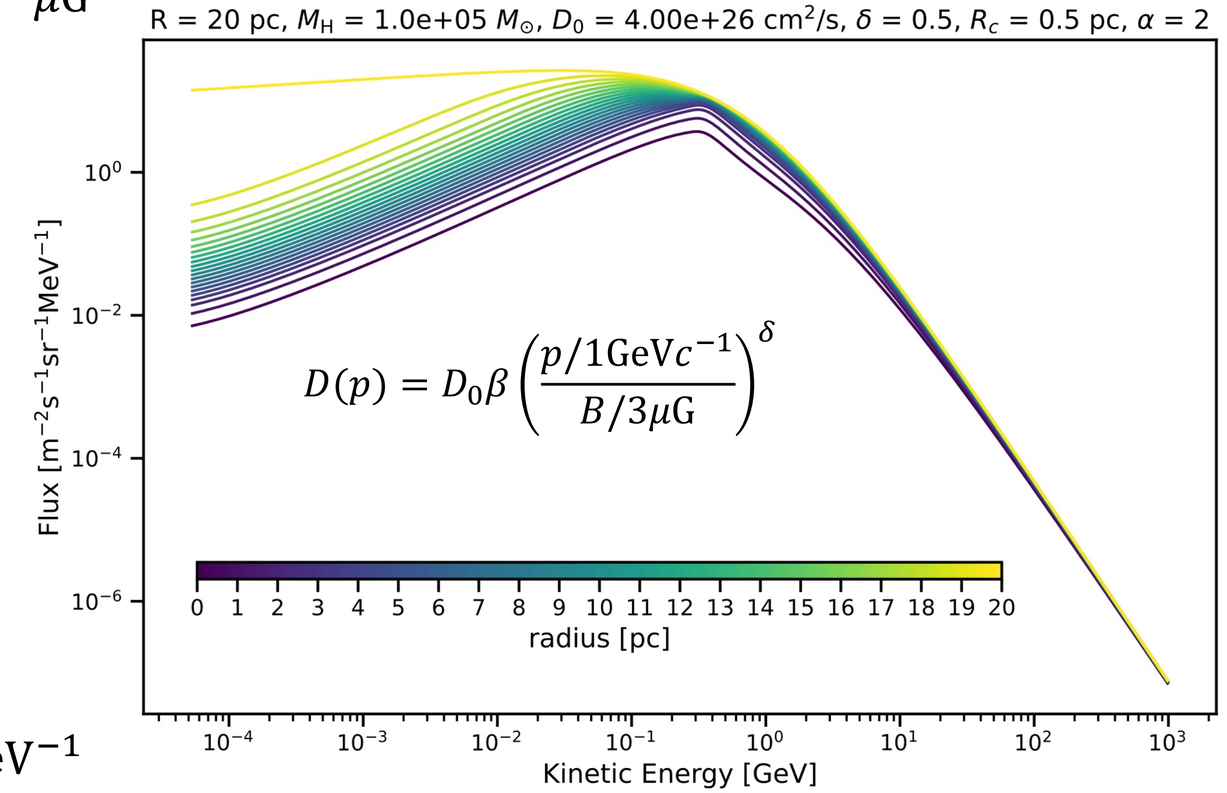
Much slower diffusion (~10^{26} cm^2/s) of CR protons in dense cores comparing to that in ISM (4e28 cm^2/s).

Study the propagation of CRs in giant molecular clouds (GMC)

Assumptions for the calculation of CR spectra in GMC (no inside CR source)

$$n_{\mathrm{H}} = n_{\mathrm{HI}} + 2n_{\mathrm{H_2}} = \frac{n_0}{1 + (r/R_{\mathrm{c}})^{\alpha}} \quad B = 10\left(\frac{n_{\mathrm{H}}}{300\mathrm{cm}^{-3}}\right)^{1/2}\mu\mathrm{G}$$



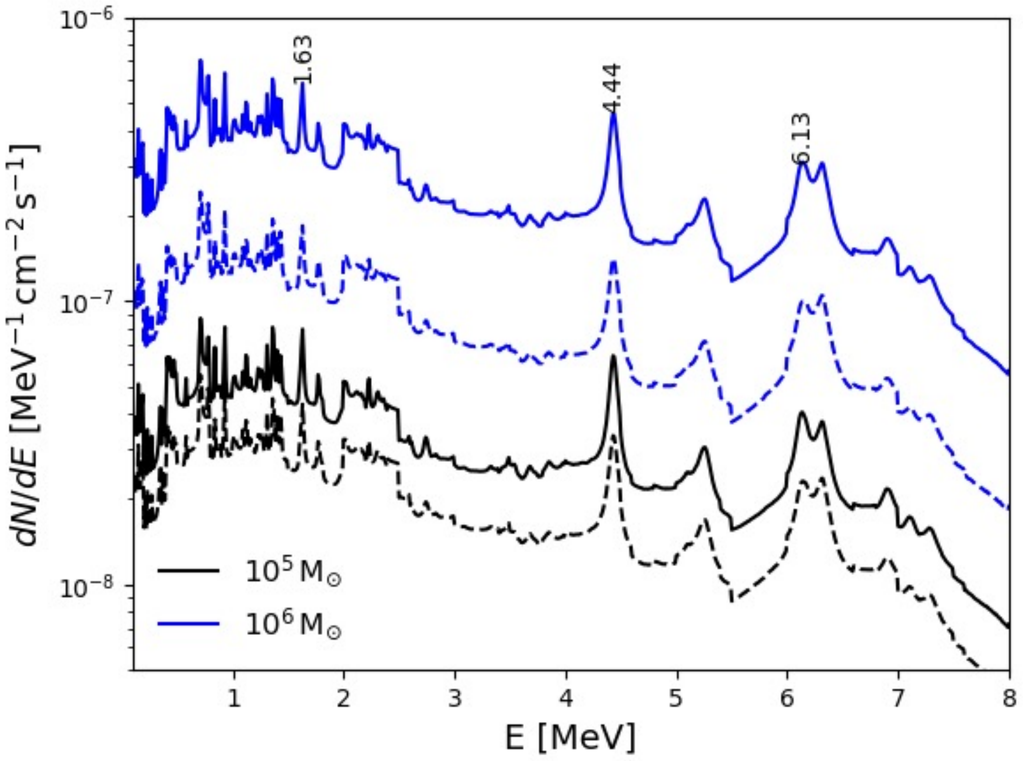


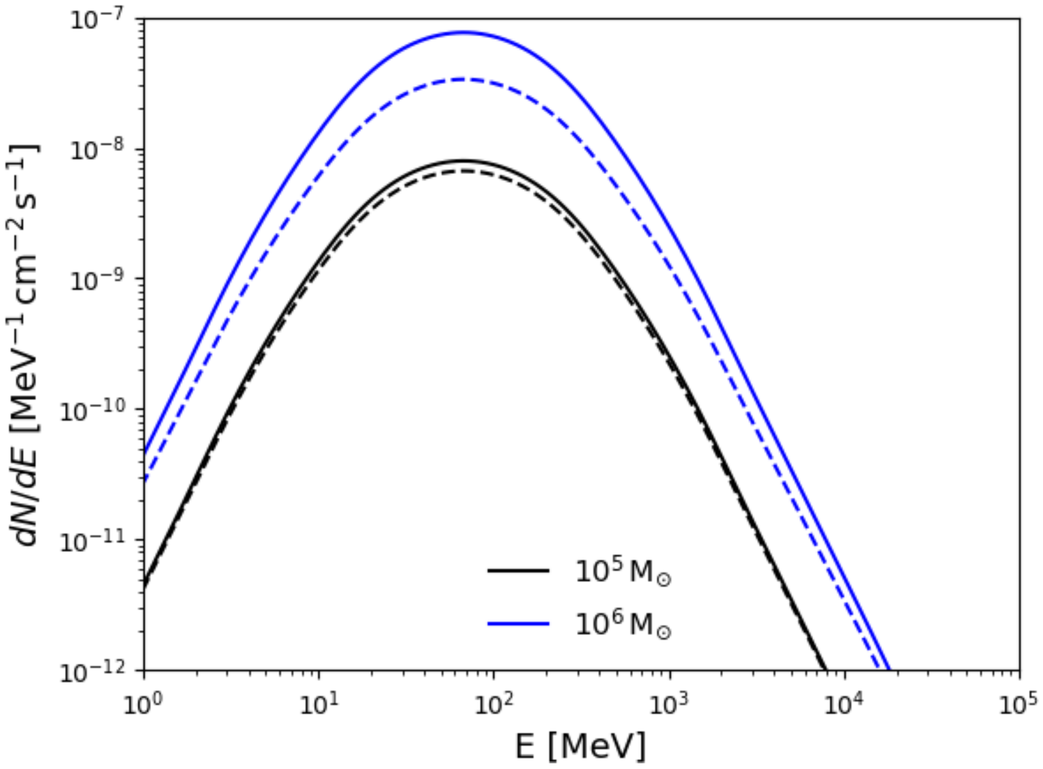
$$j_{\mathrm{LIS}}(E_{\mathrm{k}}) = 2.70\,\frac{E_{\mathrm{k}}^{1.12}}{\beta^2}\left(\frac{E_{\mathrm{k}} + 0.67}{1.67}\right)^{-3.93}\ \mathrm{m}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}\mathrm{MeV}^{-1}$$

Z.-d. Shi, B. Liu & R.-z. Yang (A&A 692,128)

Study the propagation of CRs in giant molecular clouds (GMC)

Calculated MeV nuclear de-excitation line emission and pion-decay continuum emission

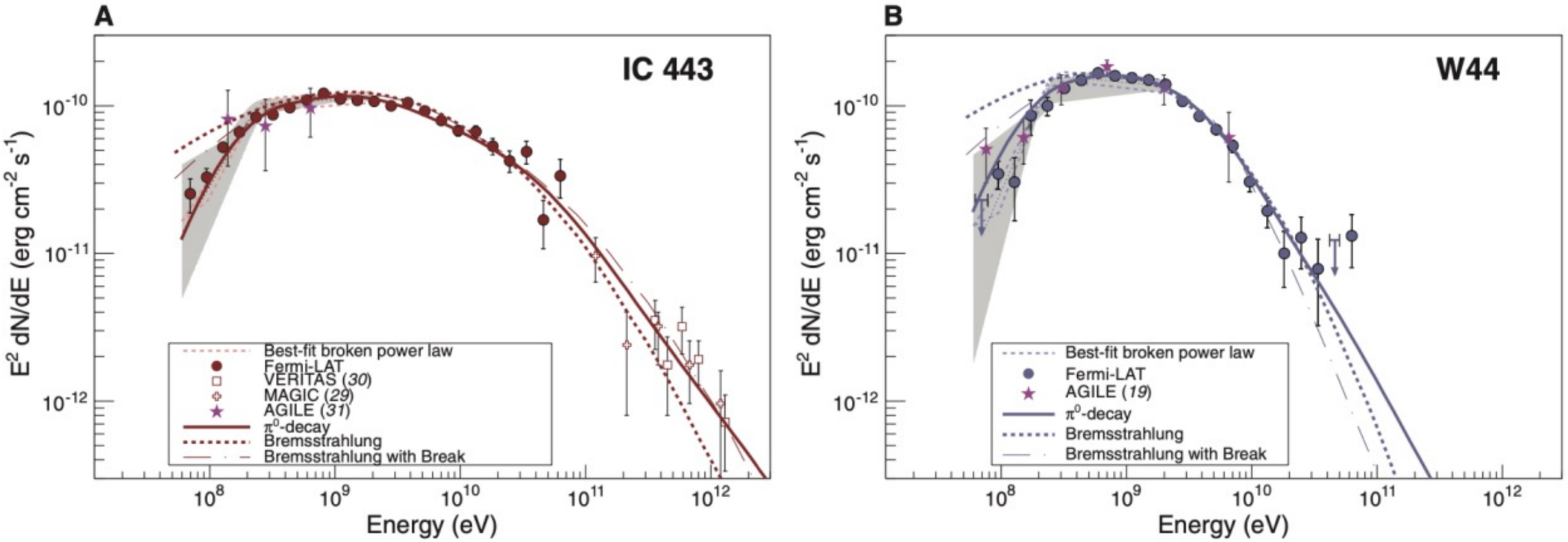




Z.-d. Shi, B. Liu & R.-z. Yang (preliminary results)

Precise measurement of pion-bump structure (in the case of W44)

“pion-bump” as the direct evidence of CR proton acceleration



(Ackermann et al. 2013)

Fermi-LAT observed pion-bump structure from SNRs, but the results are controversial.

Precise measurement of pion-bump structure (in the case of W44)

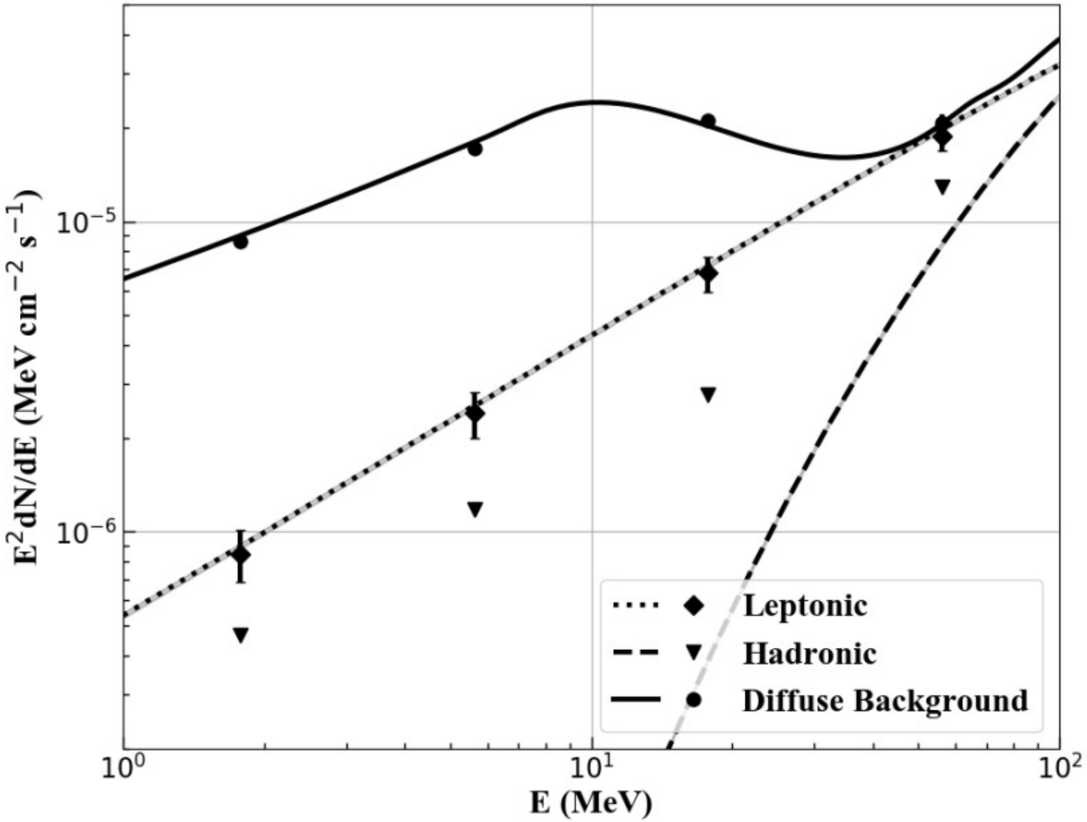
$$A_{\rm eff} = 100\ {\rm cm}^2, \text{Angular resolution}: \ 1^\circ, \ T_{\rm obs} = 2\ \text{month}$$

$$N_{\rm counts} = \int_{E_{\rm lower}}^{E_{\rm upper}} F(E) T_{\rm obs} A_{\rm eff}(E) dE$$

$$\sigma = \sqrt{N_{\rm total}} = \sqrt{N_{\rm signal} + N_{\rm bkg}}$$

$$S = \frac{N_{\rm signal}}{\sqrt{N_{\rm signal} + N_{\rm bkg}}}$$

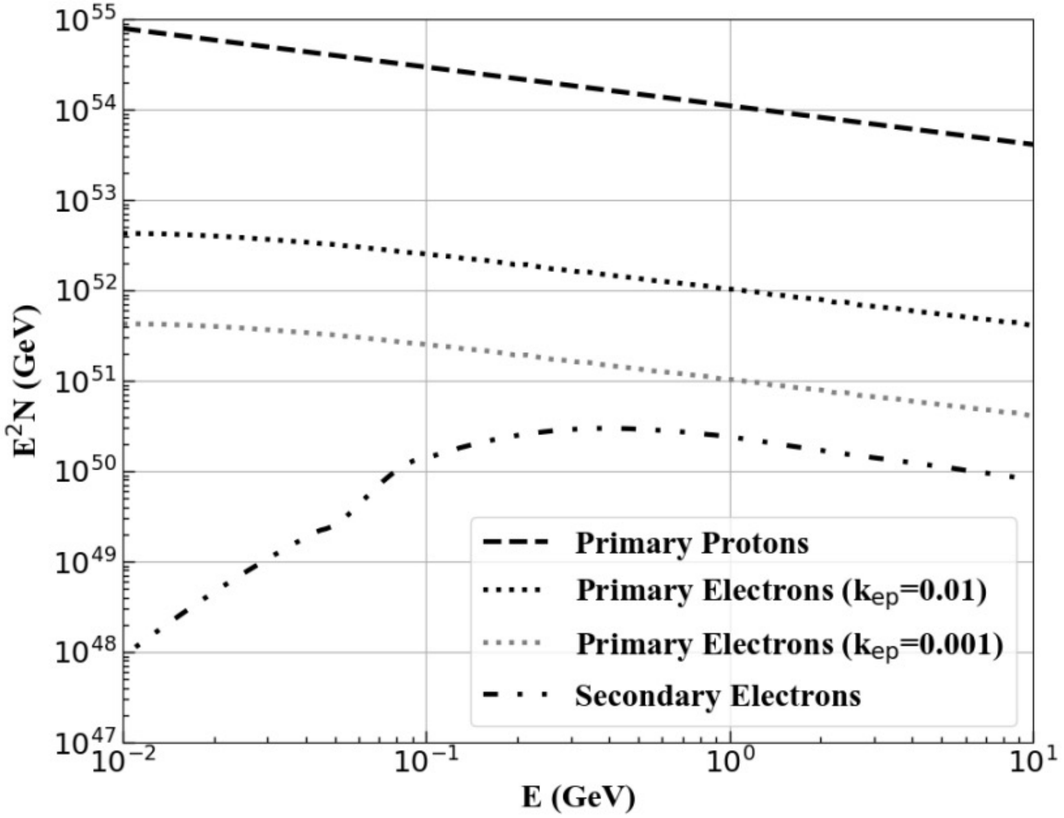
log(E/MeV)	$N_{\rm signal}$	$N_{\rm bkg}$	S (σ)
0.0-0.5	306	3099	5.24
0.5-1.0	274	1954	5.80
1.0-1.5	245	763	7.72
1.5-2.0	213	236	10.05

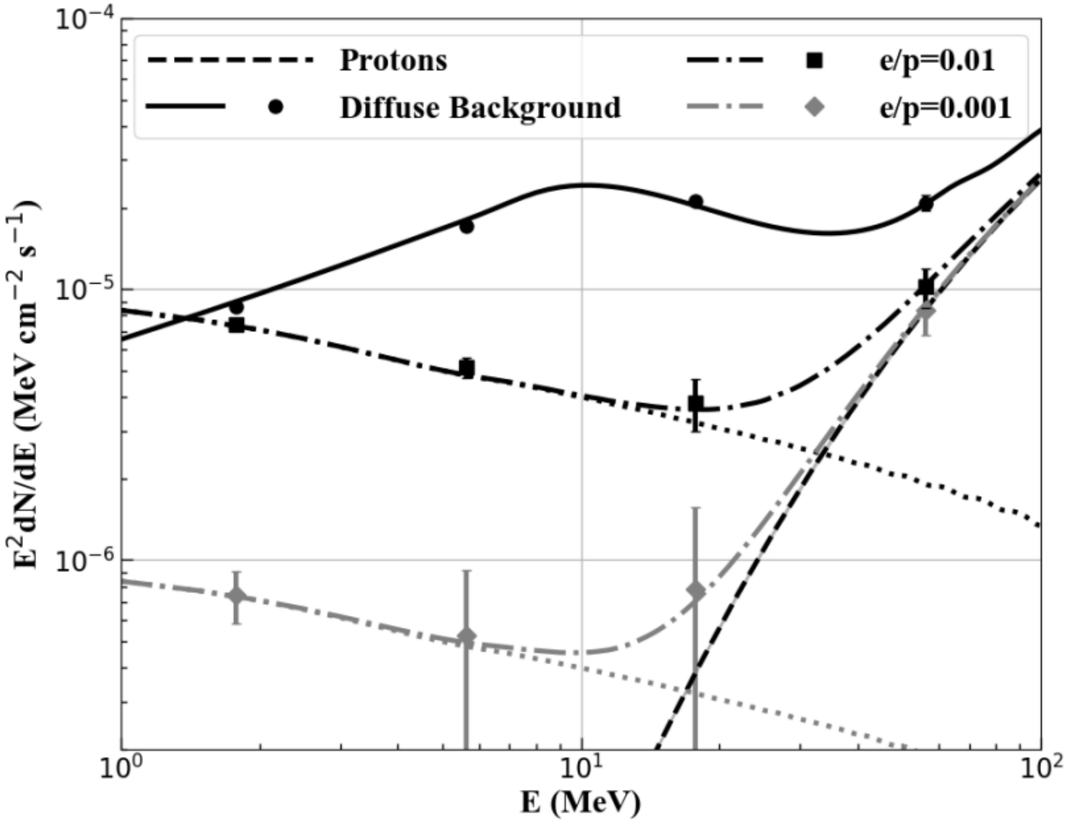


J.-h. Liu, B. Liu & R.-z. Yang, PRD (2024)

Precise measurement of pion-bump structure (in the case of W44)

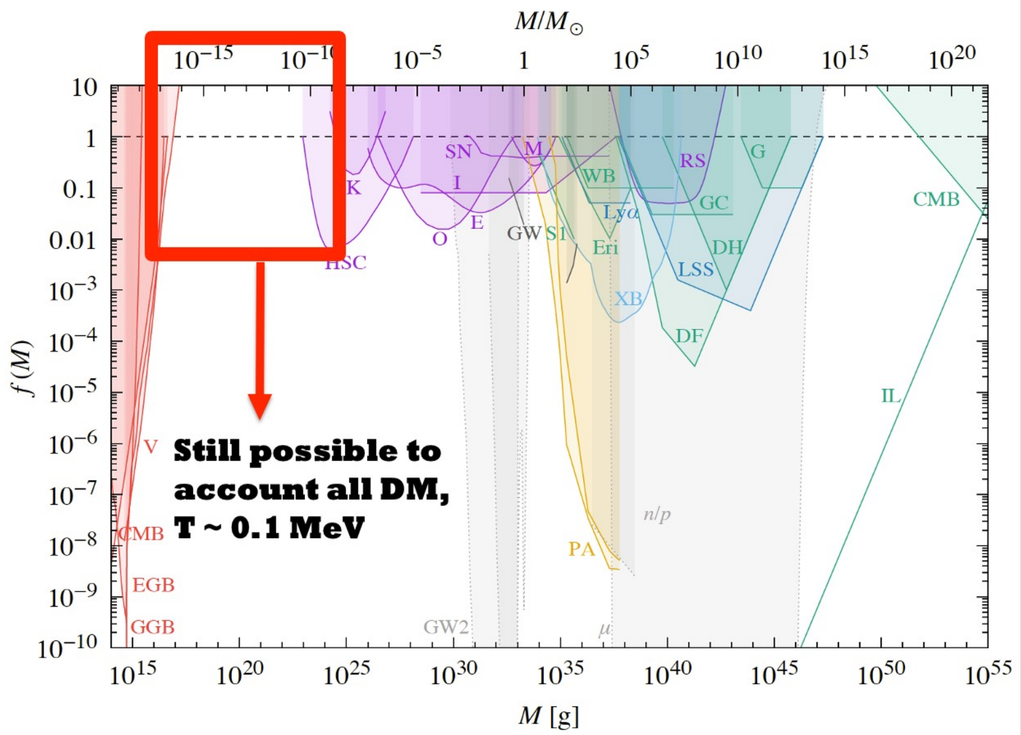
Limit e/p ratio via MeV observation

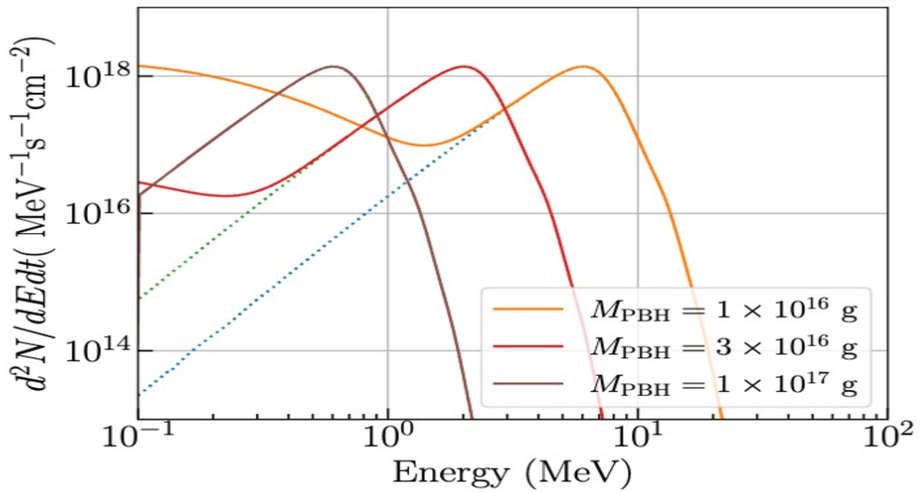


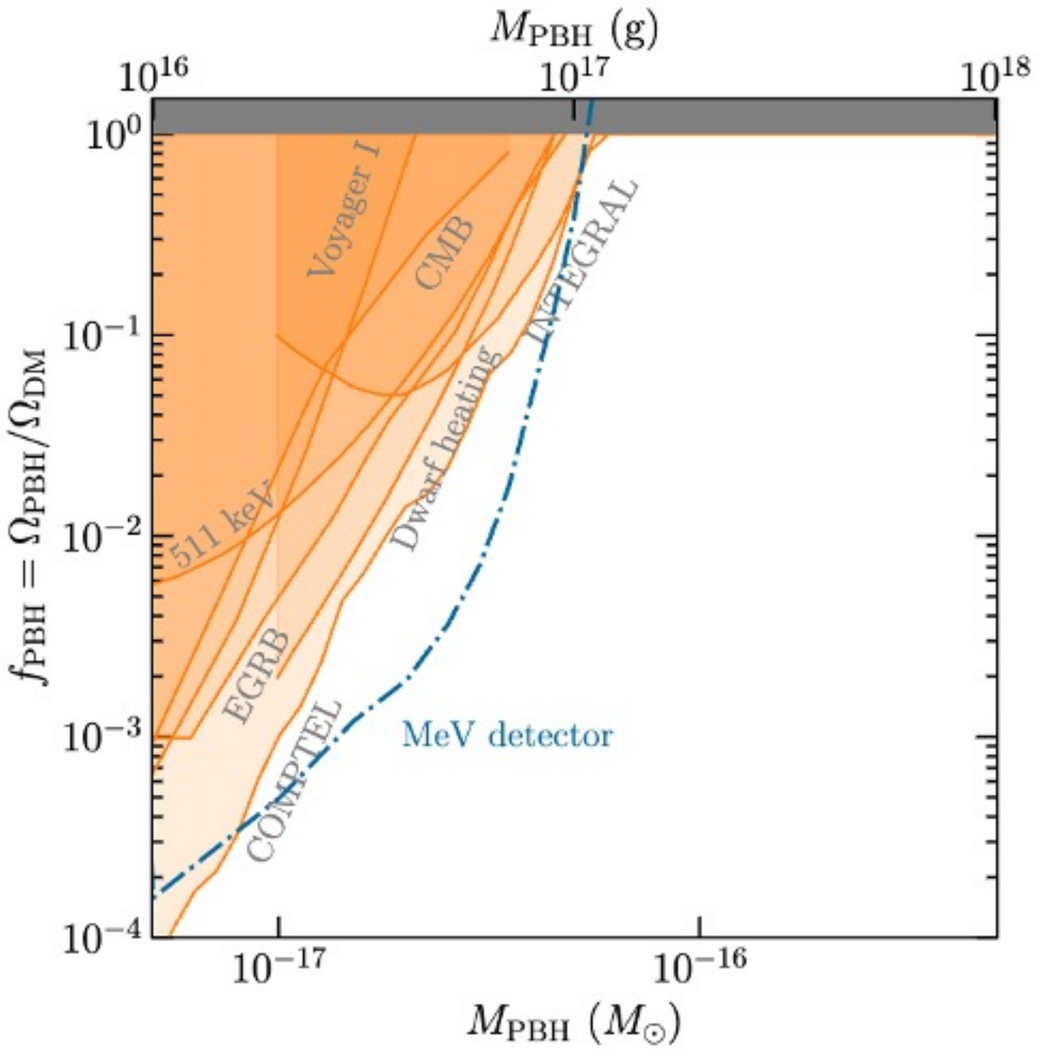


J.-h. Liu, B. Liu & R.-z. Yang, PRD (2024)

Dark Matter (Primoldial black holes)



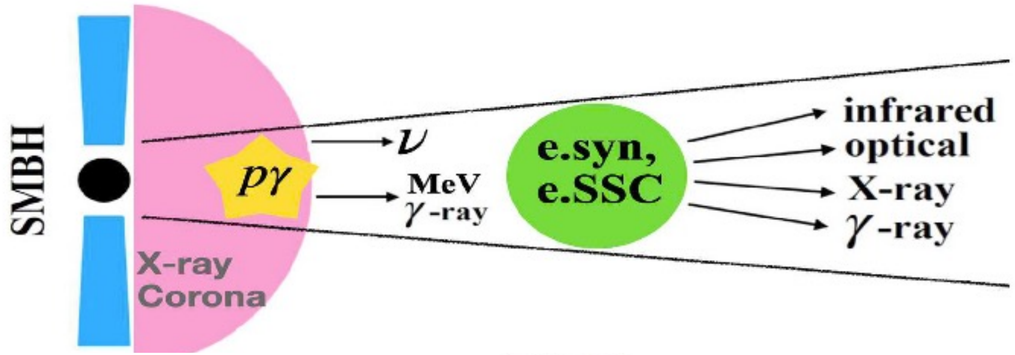




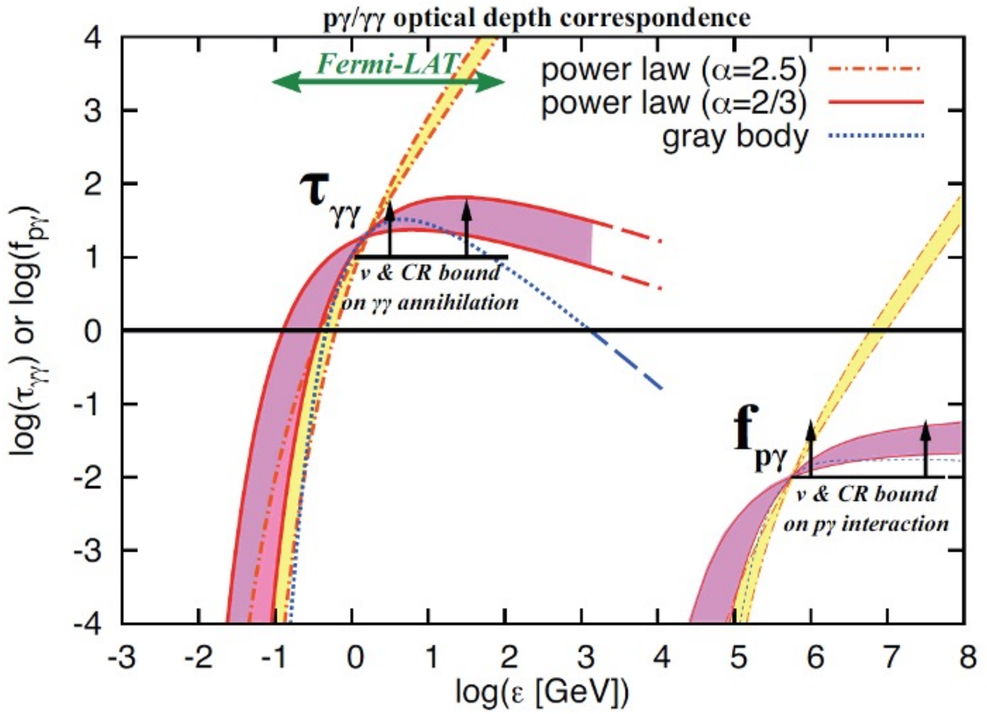
MeVGro Type detectors can set more stringent upper limit
Xie, et.al PRD (2023)

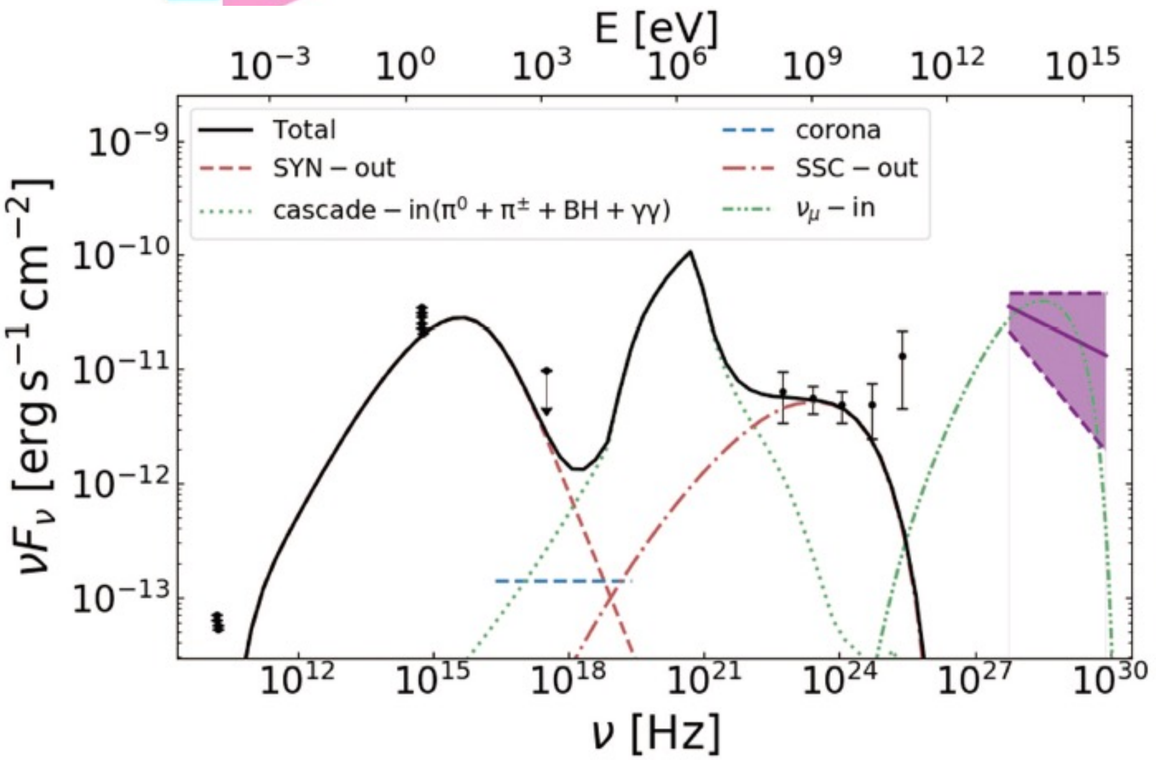
Neutrino sources

- **Neutrinos sources are probably dark in gamma-rays above GeV**
- **The associated electromagnetic cascade will have SEDs peaked at MeV**



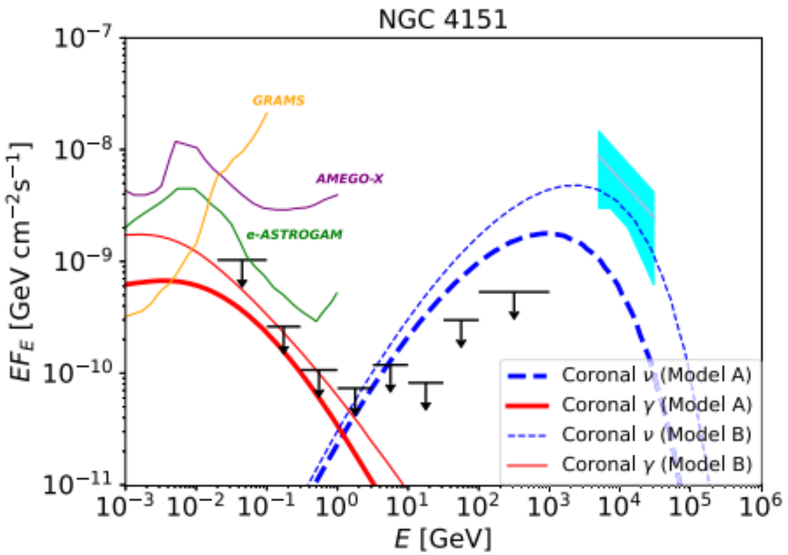
Inuoe et.al 2019, Xue et.al 2021, Murase et.al 2015

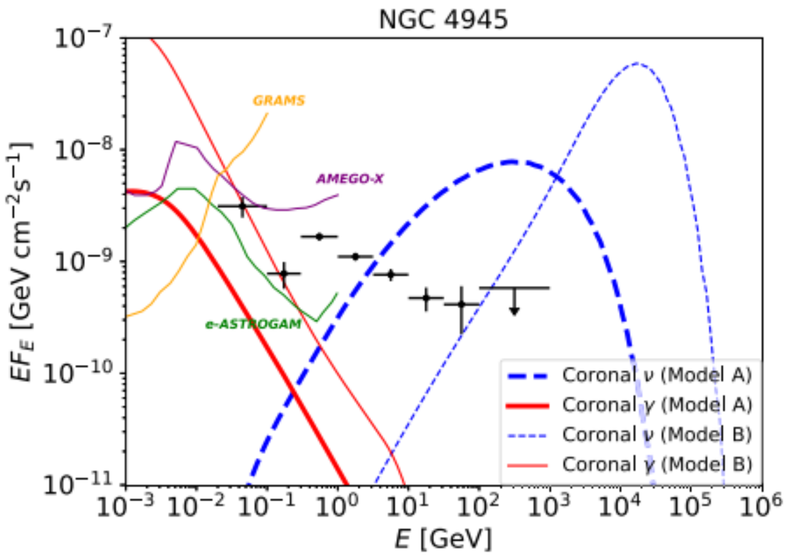


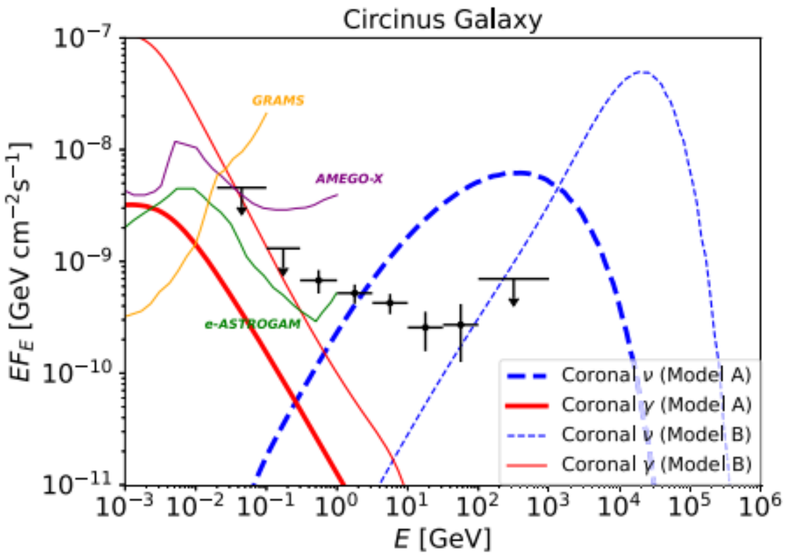


Neutrino sources

- **The associated electromagnetic cascade will have SEDs peaked at MeV**
- **Hint from Fermi LAT towards NGC 4945**





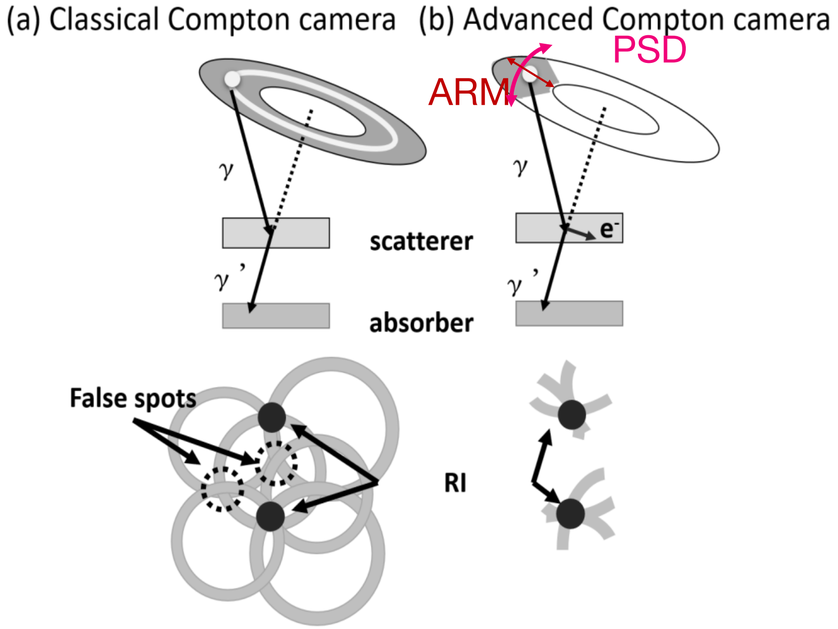


Murase et.al 2024

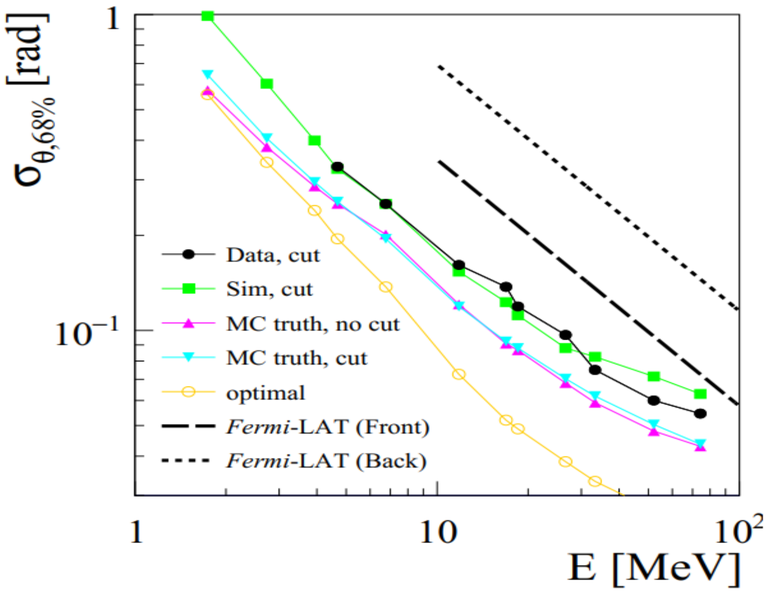
MeGaT Mission

Key technological challenges

- The energy is too high to be collimated
- It is difficult to measure 3D trajectories of electrons, that produced in Compton scattering and pair conversion according to Coulomb multi-scattering.



Astroparticle Physics 97 (2018) 10-18



It is practical to improve the e-tracking measurement by reducing the material density with gas detectors

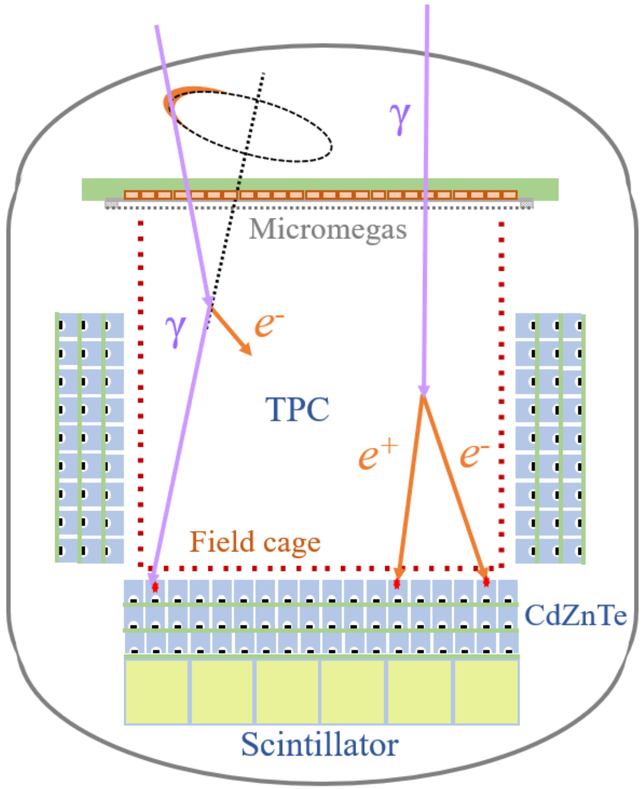
MeGAT: Conceptual design

TPC based technique

- 30 cm cubic volume（prototype）
- four 50 cm cubic or a single 100 cm ×100cm ×50(or larger)cm volume（satellite）
- 3-10 bar high pressure

Expected performance

- High dynamic range:
  0.3 MeV -100 MeV
- Angle resolution (PSF):
  2 ° @MeV, 0.5 ° @100 MeV



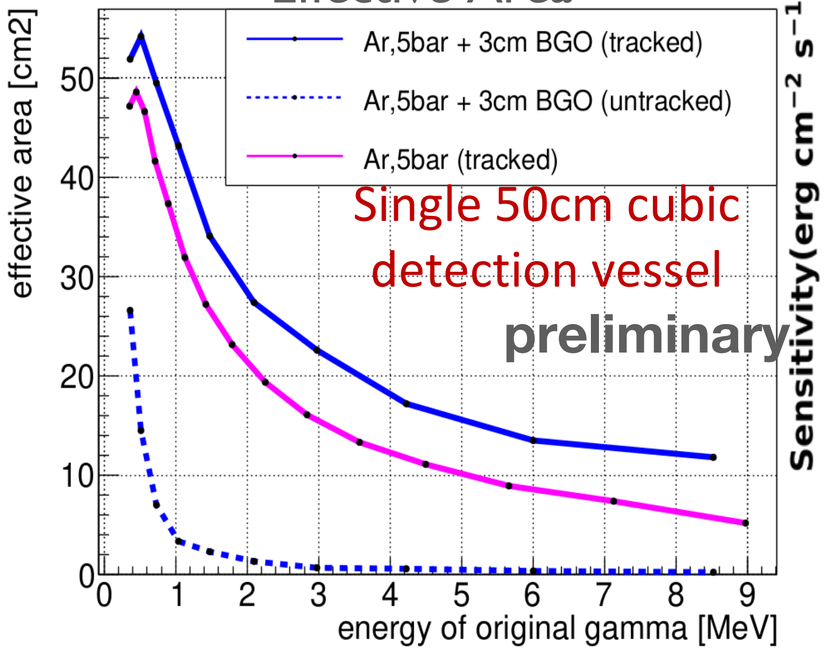
SimulatED performance

Four identical 50cm cubic detection vessels

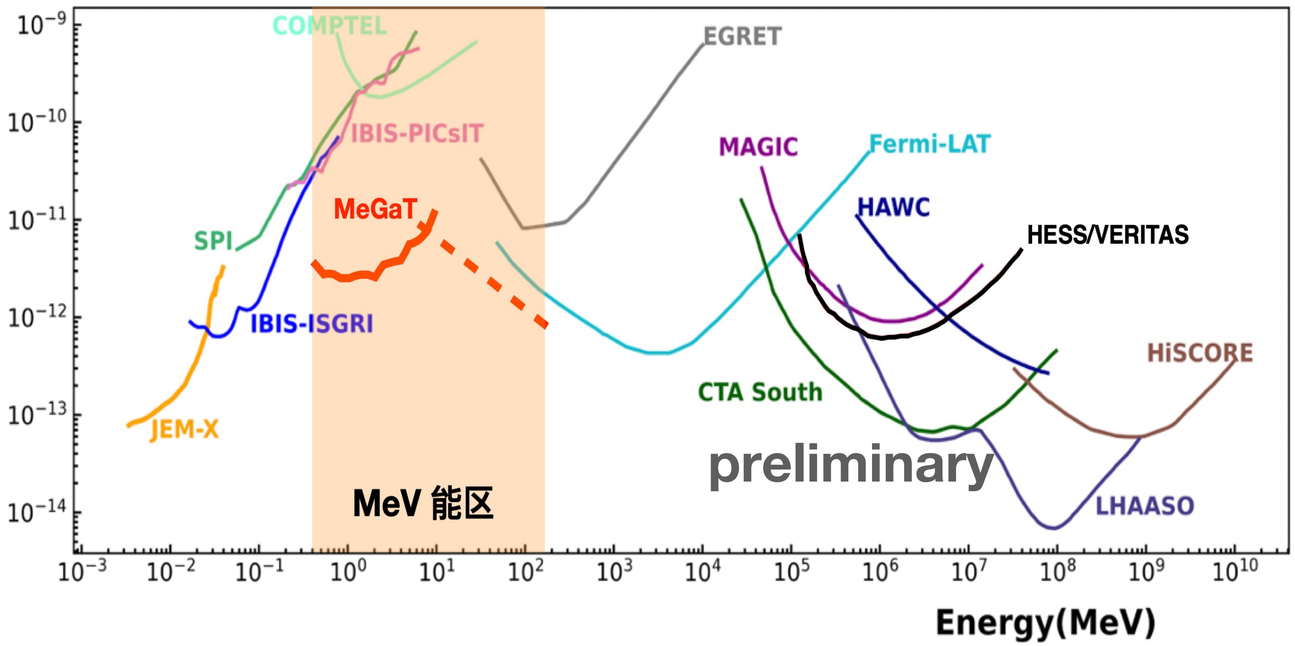
—— Very preliminary simulation result without pair conversion

-------- Rough estimation by taking pair into account

Effective Area



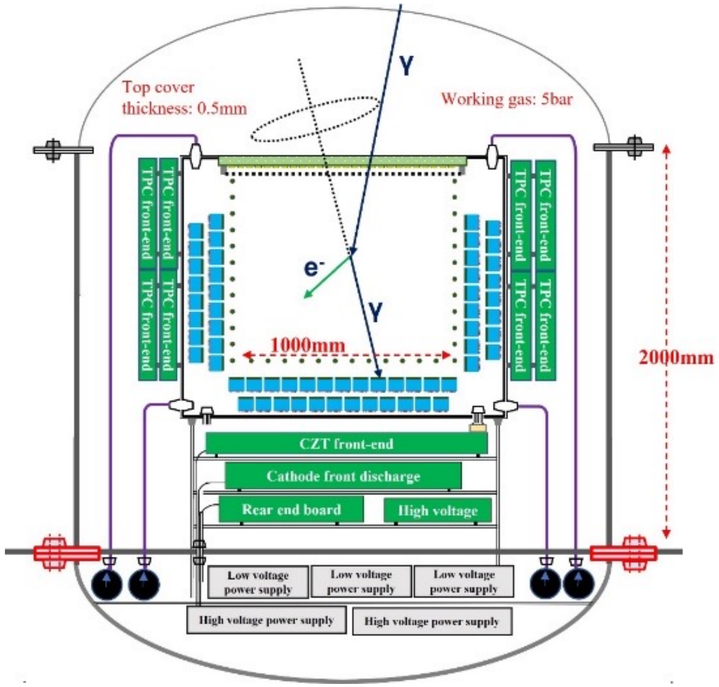
Sensitivity of MeGaT ($N_\sigma = 3\sigma$, $T = 1yr$)

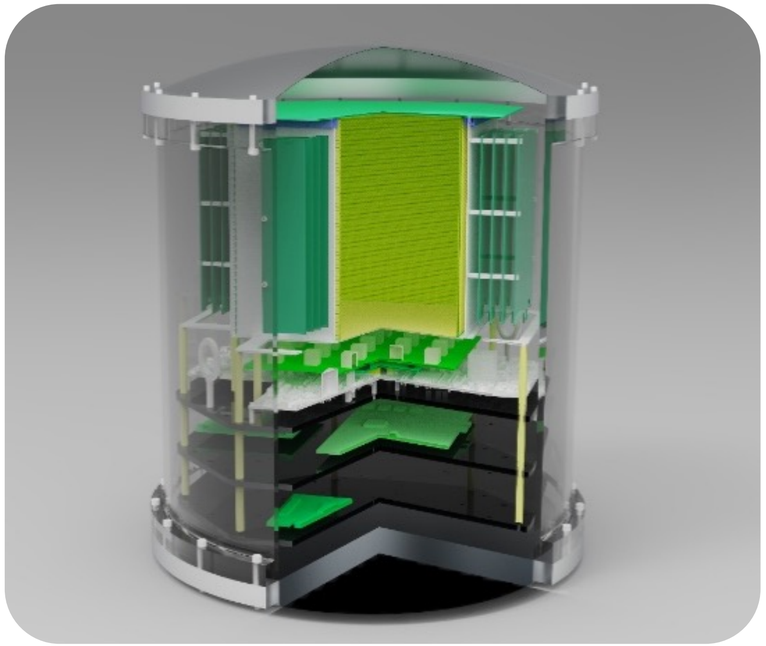


Perfect performance on spatial and energy resolution are required for the TPC and calorimeter

Prototype of R&D

- 30 cm cubic volume



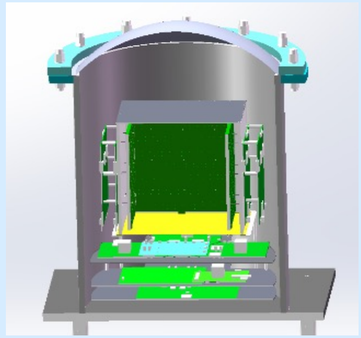


Technical challenges

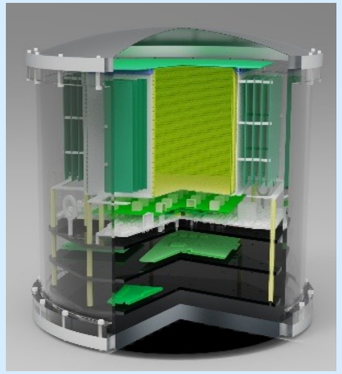
- High voltage: Micromegas ~ 3000V，Field cage ~ 15000V
- High-pressure sealing: 0.5 Mpa
- Mechanical support and heat dissipation issues

MeGaT: 30cm prototype

Tank

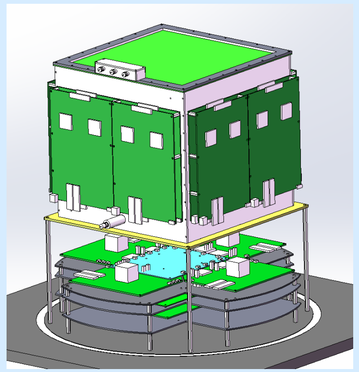
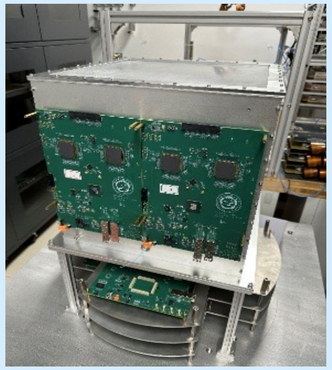


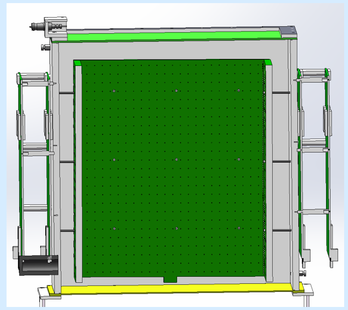

P > 5 Bar




0.4mm thick Stainless steel window on top

Inner TPC




Mechanical and supports

MeVGRO and PAIRS

MeVGRO（女娲, NuWa）

(MeV Gamma-Ray Observatory)

Aim to observe 0.2~5MeV (extendable to 100 MeV) gamma-rays in wide-field

-Energy : nuclear lines and continuum
-Imaging
-Timing
-Polarization

- *Proposed by IHEP to Chinese Academy of Sciences (CAS) in 2017.*
- **Concept research funded by CAS (~2020)**
- **Prototype development funded by NFSC and CNSA (~2024)**
- **Proposed to CAS as a candidate mission for Intensive Study in 2022**

Collaboration: PMO, THU, NPU, BUAA, SU, Microsat

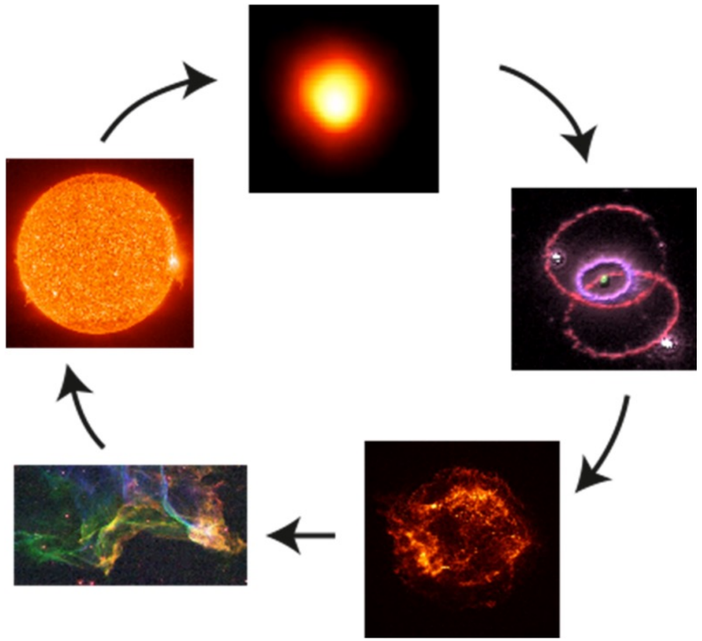


Sensitivity is expected to be improved by 1~2 orders of magnitude

MeVGRO Science

Core objectives

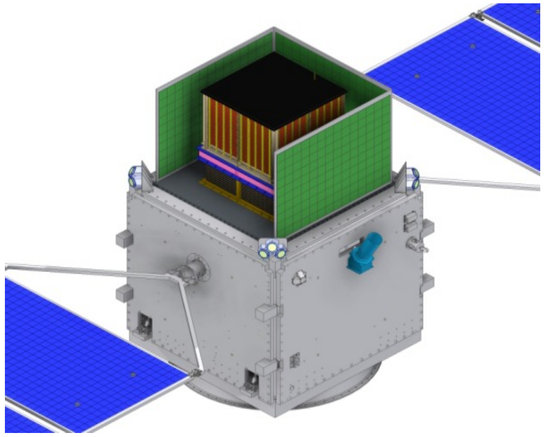
- Supernova Explosion Mechanisms
- Heavy-element Formation and Evolution
- Indirect Search of Dark Matter

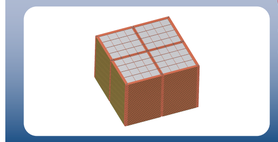


Gamma-ray Line (keV)	Nuclide (half-life)	Sources
158/812	^{56}Ni (6d)	SNe Ia /CCSNe
511/847/1238	^{56}Co (77d)	
122	^{57}Co (270d)	
68/78/511/1157	^{44}Ti (78yr)-^{44}Sc (4h)	SNR
511/1809	^{26}Al (0.7Myr)	
1173/1332	^{60}Fe (2.6Myr)-^{60}Co (5.3yr)	
511	^{106}Ag (24min)	NS Merger
88/415/666/695/721	^{126}Sb (12d)-^{126}Sn (0.23Myr)	
100	^{245}Cm (8.5kyr)	
2600	^{208}Tl (3min)	
478	^{7}Be (53d)	Novae
511/1275	^{22}Na (2.6yr)	
511	e+ e-	Diffuse
1173/1332	^{60}Co (5.3yr)	
1809	^{26}Al (0.7Myr)	

MeVGRO payloads

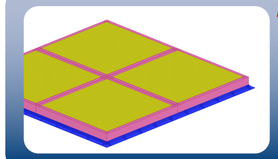
Aim to observe 0.3~3MeV(100MeV) gamma-rays in wide-field





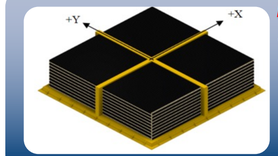
Gamma-ray converter tracker(GCK)

- *50 layers DSSD*
- *Converter and tracker*



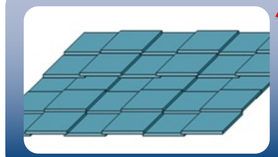
Low Energy Calorimeter(LECA)

- *3D CZT (2 layer)*
- *Precise energy measure, Compton camera*



High Energy Calorimeter(HECA)

- *Scintillators(CeBr3 or new material)*
- *Absorber, high energy measure*



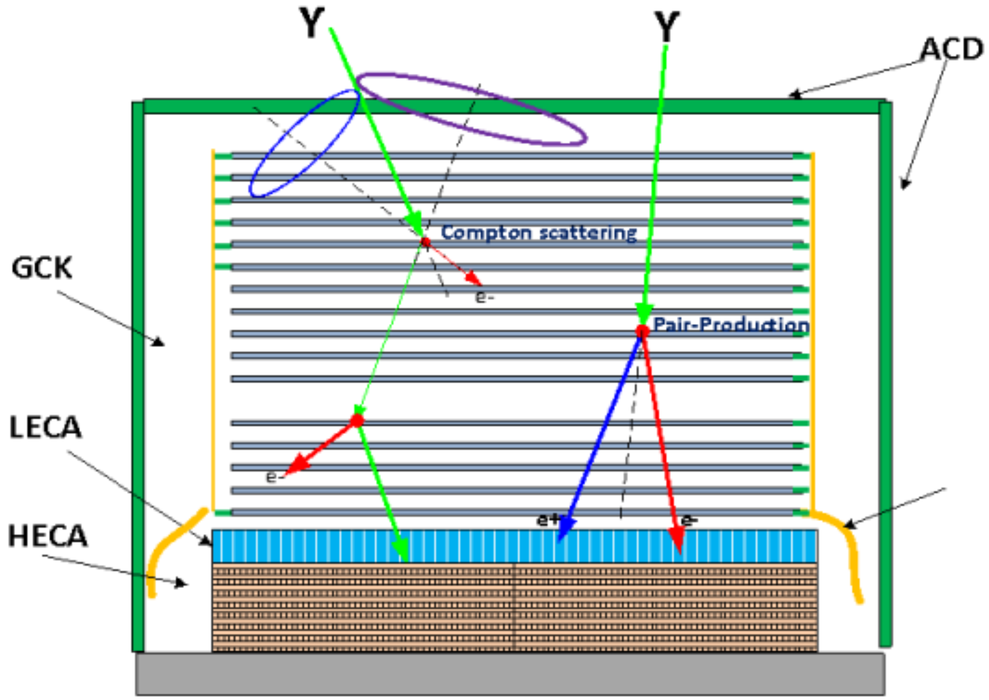
Anti-concident Detector (ACD)

- *PSD+MAPMT, Veto for charge particles*



Cosmic burst monitor(CBM)

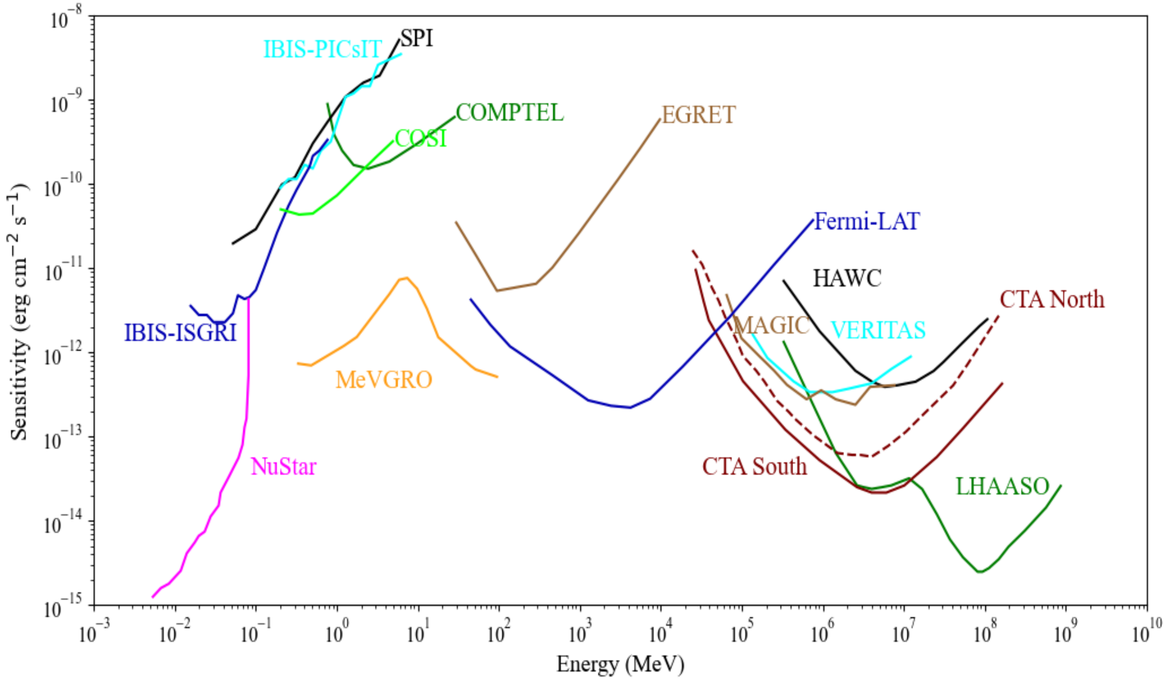
- *LaBr3+SiPM array*



MeVGRO expected performance by simulation

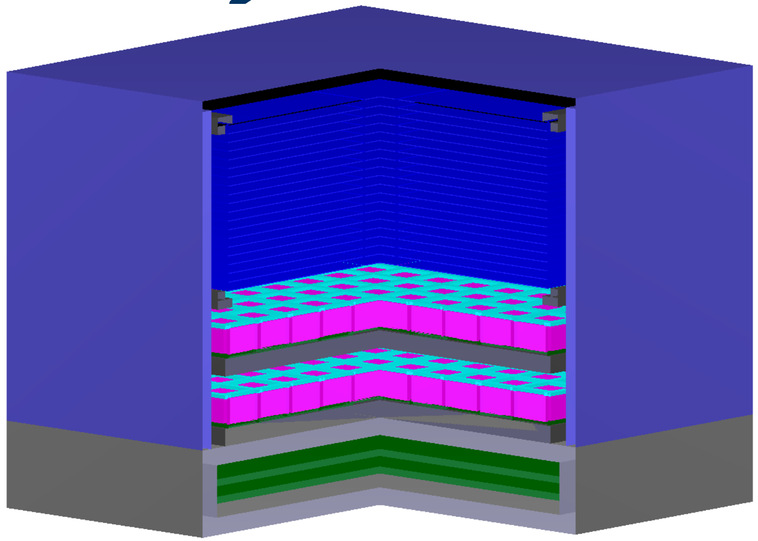
	Performance
Energy range	0.3~3MeV(100MeV) (8keV~3MeV for CBM)
FOV	3.6 sr (±65°), Imaging
Angular resolution	~2°@1MeV, 100MeV (FWHM)
Effective area	~1000cm²@1MeV，100MeV （3σ）
Energy resolution	<1%@662keV(by CZT)
Continuum Sensitivity	~2.0E-12 erg/cm²/s@1MeV,100MeV (5yrs survey)
Lines sensitivity	~2.48E-06 ph/cm²/s@0.511MeV ~9.56 E-7 ph/cm²/s@1.8MeV (5yrs survey)
MDP（polarization）	<15% (<2MeV) (10mCrab, 5yrs survey)

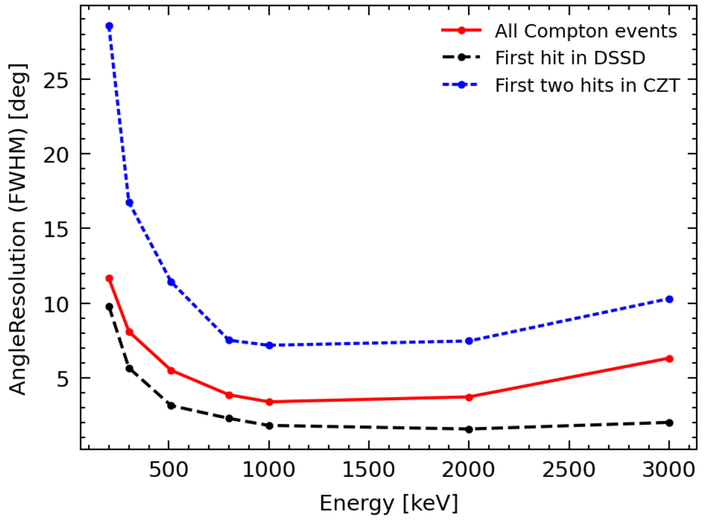
Energy (keV)	SPI (ph/cm²/s)	COSI (ph/cm²/s)	MeVGRO (ph/cm²/s)
511	5E-4	7.9E-6	2.48 E-6
1809	1E-4	1.70E-6	9.56 E-7

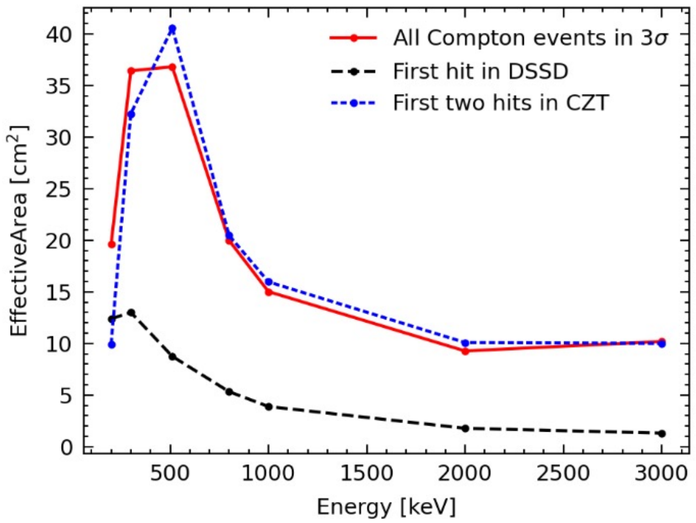


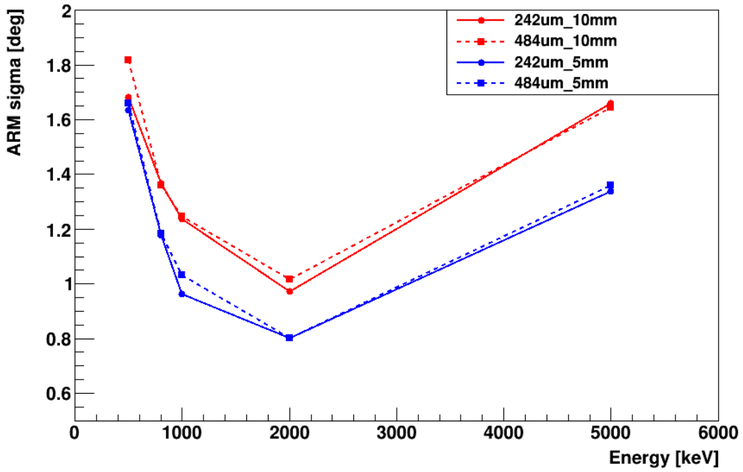
MeVGRO Prototype (2025~2028)

- GCK: 2*2 DSSD (20cm*20cm)--10 layers
- LECA: 1 layer (8*8) CZT
- HECA: 1 layer scintillator array





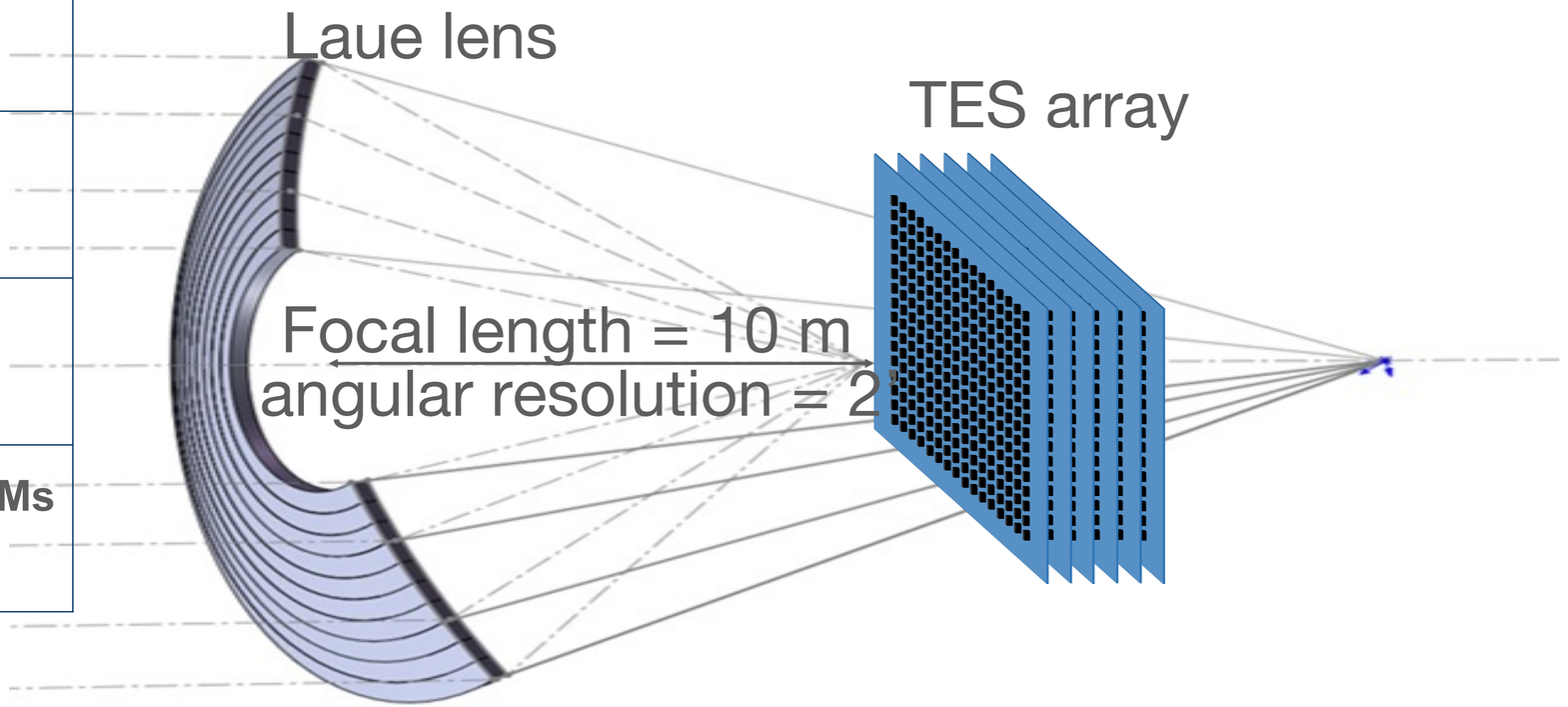




PAIRS Project （2025-2029）

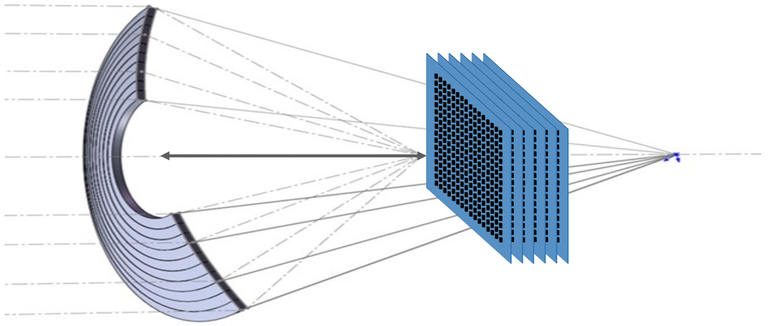
Positron Annihilation Imaging high-Resolution Spectrometer

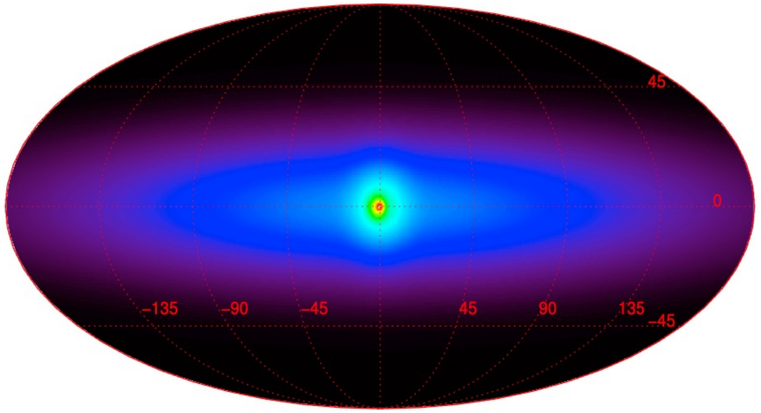
	Performance
Energy range	450 keV ~ 550 keV
Angular resolution	~2 arcminutes @511keV
Energy resolution	<0.1%@511keV
Lines sensitivity	~1.E-06 ph/cm^2/s@0.511MeV(1Ms)



Laue direct imaging + superconducting microcalorimeter

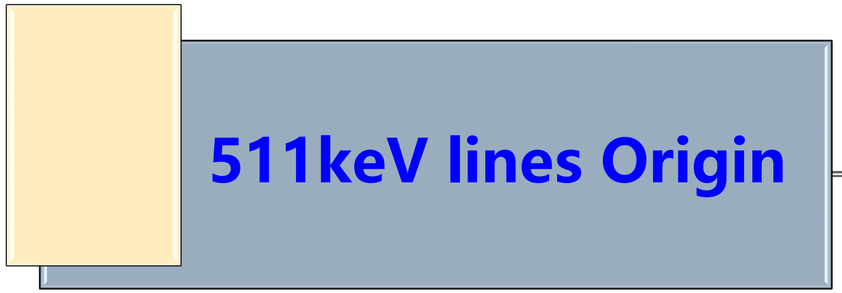
PAIRS Science





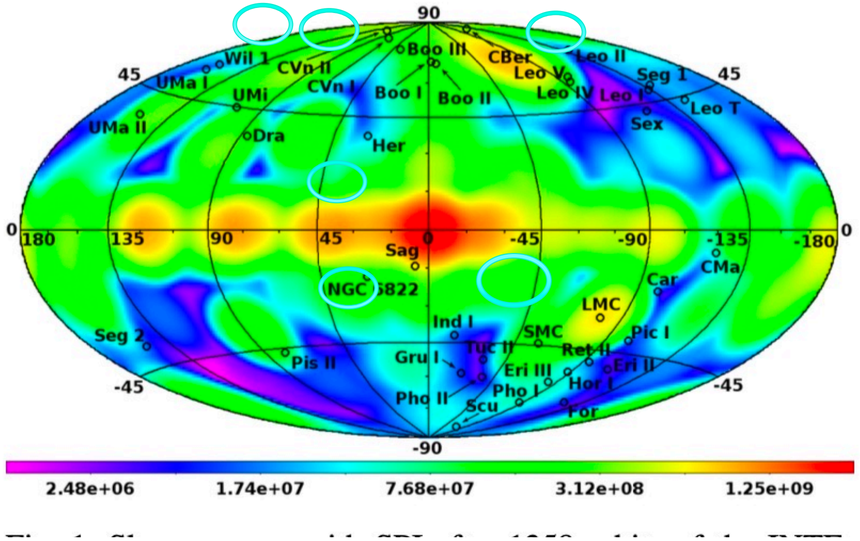
Galactic Center

Core objectives



Astrophysical sources

New Physics



Dwarf Galaxies

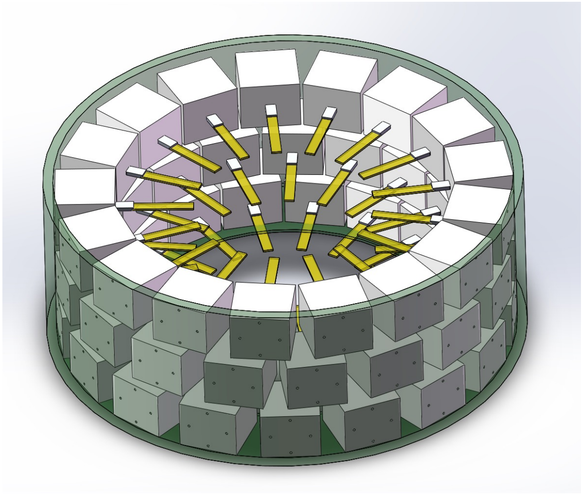
Laue Lens Optics

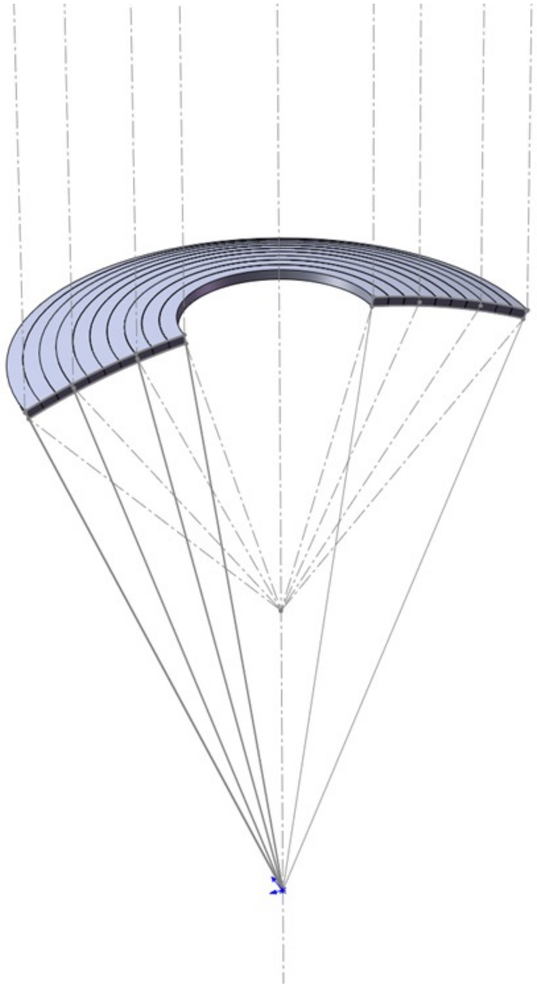
Design

- Material of focus lens: Ge (111)
- Energy range: 450 keV ~ 550 keV
- Field of view: 5 arcmin
- Spatial resolution: 2 arcmin (5.8 mm)
- Pointing accuracy: 15 arcsec
- Pointing stability: 10 arcsec
- Focus area: 100 cm^2
- Focus length: 10 m
- Size: diameter 40 cm * 30 cm
- Working temperature: 20±5℃

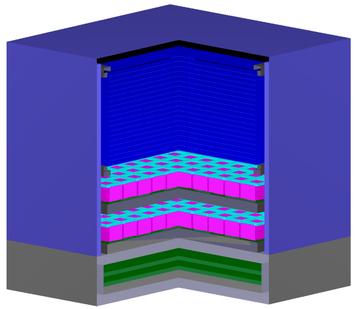
Current status

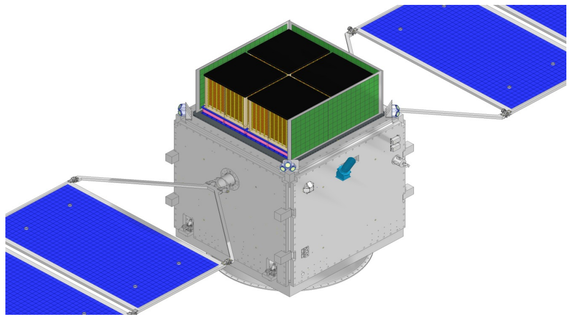
- Completed active optics design
- Mastered anodic bonding technique, ready to implement on Laue bent crystals





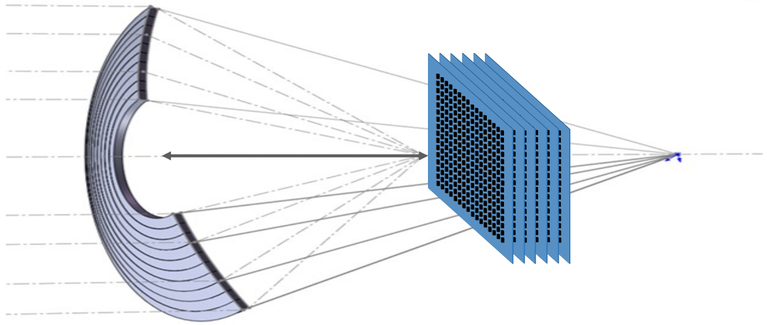
Outlooks-development plan

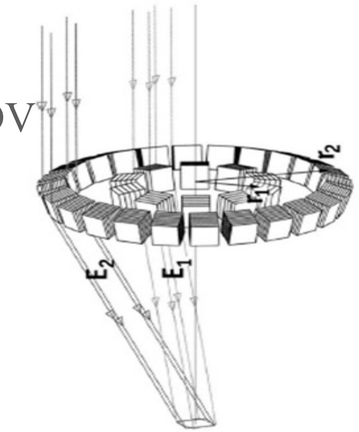


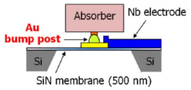


MeVGRO & MeVGRO prototype
(MeV Gamma-Ray Observatory)

0.2–5 MeV (extendable to 100MeV); large FOV







PAIRS
(Positron Annihilation Imaging high-Resolution Spectrometer)

511 keV high angular & energy resolution

FIONA
(Focusing Imager Of Nuclear Astrophysics)

0.1–2 MeV; high angular resolution; high lines sensitivity

Late 2020s
–MeVGRO prototype
–PAIRS (balloon/satellite)

2030s and beyond
– MeVGRO
– FIONA (satellite)

Conclusions

- MeV astronomy is the most proper window to study LECRs

- important link between CR with other fields of astronomy

- On going MeV projects in China:

Megat: TPC (gas detector), better angular resolution

MeVGRO: semi-conductor tracker, larger effective area

PAIRS: Laue Lense, best angular resolution but limited energy range